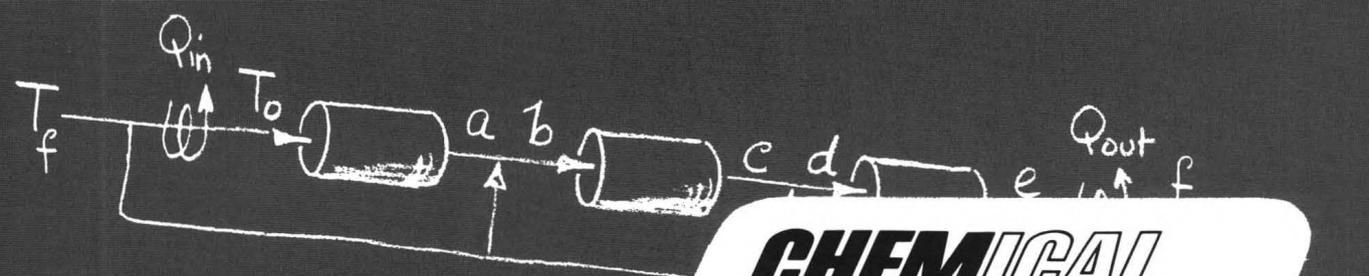
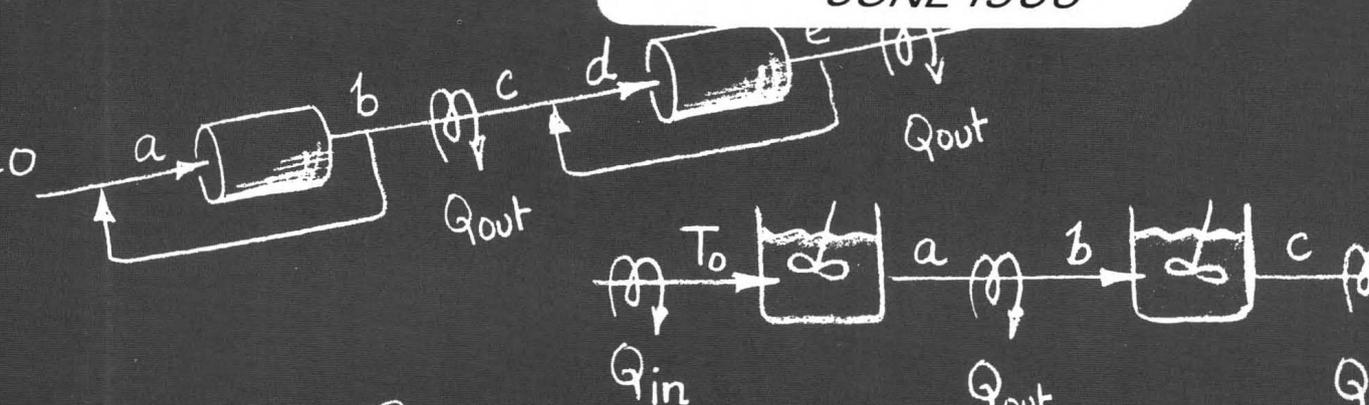


CHEMICAL ENGINEERING EDUCATION

JUNE 1966

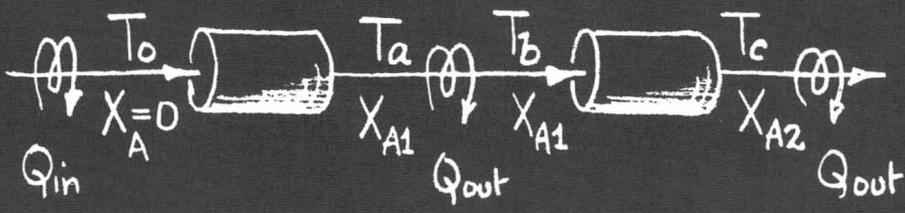
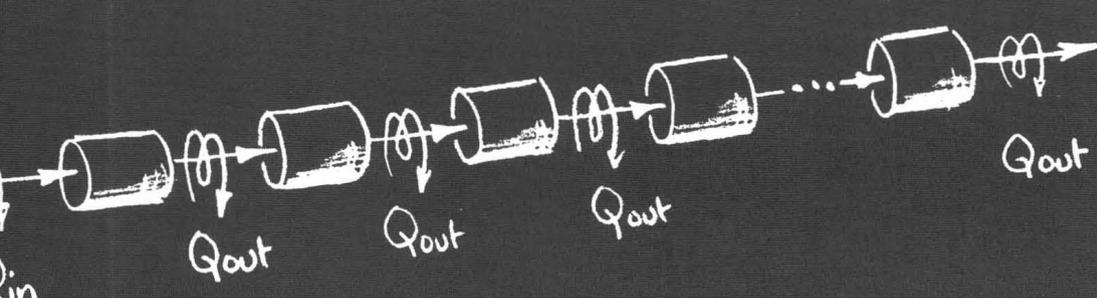


$$r(T, C_A) = k C_A = k_0 e^{-E/RT}$$



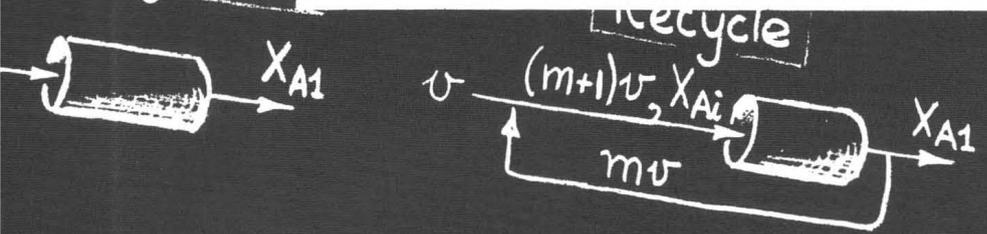
a... Pure gaseous reactant, use backmix

b... 1% reactant, use plug flow

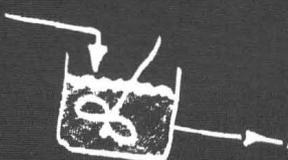


CHANGING ATTITUDES TO REACTOR DESIGN

Plug Flow



Backmix





chemical engineering texts from Prentice-Hall

New for 1968 . . .

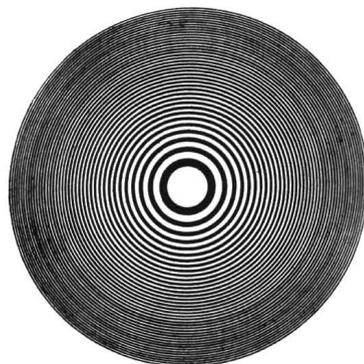
INTRODUCTION TO FLUID MECHANICS by Stephen Whitaker, University of California at Davis. Provides an exceptionally thorough treatment of the macroscopic (or integral) momentum and mechanical energy equations. February 1968, approx. 480 pp., \$12.00

MATHEMATICAL METHODS IN CHEMICAL ENGINEERING: MATRICES AND THEIR APPLICATION by Neal R. Amundson, University of Minnesota. Outlines the elementary theory of matrices discussing eigenvalue problems, Hamilton-Cayley's theorem, and systems of linear differential equations and algebraic equations. 1966, 270 pp., \$12.50

FOUNDATIONS OF OPTIMIZATION, by Douglass J. Wilde, Stanford University and

Charles S. Beightler, University of Texas. Covers both the direct and indirect optimization techniques; extends the new non-linear technique of geometric programming to functions with negative signs and reversed inequalities. 1967, 480 pp., \$12.95

KINETICS OF CHEMICAL PROCESSES by Michel Boudart, Stanford University. Explains the kinetic analysis of elementary steps, single reactions, and reaction networks for chemists interested in reactivity and chemical engineers interested in reactors. April 1968, approx. 220 pp., \$7.50



For approval copies, write: box 903

PRENTICE-HALL

Englewood Cliffs, New Jersey 07632



Contents for Volume 1, No. 4, June '66

55 Changing Attitudes To
Reactor Design

O. Levenspiel

70 The Chemical Engineering
Approach To Entropy

J. L. Throne

72 The Integrity of
Chemical EngineeringJ. M. Douglas
and S. A. Miller

DEPARTMENTS

iii Editors' Corner

63 Speaking Out R. G. Thorpe

Chemical engineering curricula today face the sternest confrontation of their entire history, a challenge from inside the world of engineering itself that amounts to questioning their *raison d'être*. Yet if the discipline of chemical engineering is reality and if the chemical process industry is not illusion, there should be no doubt about the reasonable purpose of chemical engineering education. The core of that purpose is three-kernelled: *to prepare its graduates at all levels to solve the engineering problems of chemical processing, from research to marketing; to provide clear educational leadership in chemical engineering in both academic and industrial spheres; and to share strongly the technical leadership of chemical engineering.* The central kernel is, of course, the first.

A not inconsiderable piece of the student's equipment with which his chemical engineering education should outfit him is attitude. He must be conditioned to seek creative solutions to complex, real-world problems. He must be able to look at whole systems and not merely the components thereof. He must be stimulated to sustain a lifetime of continued learning. And he must be aware of his field, recognize its power, and sense the satisfaction it can yield to its practitioners. Indeed, perhaps the most significant burden laid upon late-twentieth-century faculties of chemical engineering is one of attitude. We who teach must impress our undergraduate and graduate students with the imperative of continued scholarship and the reward that goes with it. We must find ways to encourage disciplined originality. Above all, we must reflect the genuine excitement of the real-life engineering problem. Without such inspiration, our students can be expected to view the world of chemical engineering toward which their college experience should direct them with mild interest at best, and possibly with distaste. The persistent maintenance of infectiously zestful attitude is a demand of inestimable importance that we educators cannot evade.

CHEMICAL ENGINEERING EDUCATION

The official journal of the Chemical Engineering Division, American Society for Engineering Education

Editor	Shelby A. Miller
Consulting Editor	Albert H. Cooper
Assistant Editor	John W. Bartlett
Publications Committee of CED	
L. Bryce Andersen	Chairman
Charles E. Littlejohn	
E. P. Bartkus	
James H. Weber	
Executive Committee of CED	
Chairman	John B. West
Chairman-elect	J. A. Bergantz
Secretary-Treasurer	William H. Honstead
Elected Committeemen	J. T. Banchemo
	W. H. Corcoran
Past Chairman	George Burnet

CHEMICAL ENGINEERING EDUCATION is published four times during the academic year by the Chemical Engineering Division, American Society of Education. Publication months: October, January, April, June. Publication and editorial offices: 201 Gavett Hall, University of Rochester, Rochester, N. Y. 14627. Title registered U. S. Patent Office.

Subscription rates: To Chemical Engineering Division members, \$3.00 per year; to non-members in the Western Hemisphere, \$4.00 per year; to non-members outside the Western Hemisphere, \$5.00 per year; single issue price, \$1.50. Advertising rates quoted upon request.

FOURTH ANNUAL
CHEMICAL ENGINEERING DIVISION
LECTURESHIP AWARD

to

Dr. Octave Levenspiel

THE CHEMICAL ENGINEERING Division Lectureship Award of the American Society for Engineering Education is an annual award of \$1000 to a distinguished engineering educator for outstanding achievement in fundamental chemical engineering theory or practice. It is sponsored by the 3-M Company.

The recipient of the Fourth Annual Award, presented on June 22, 1966, was Octave Levenspiel, Professor of Chemical Engineering at Illinois Institute of Technology, who responded with an address on "Changing Attitudes to Reactor Design." Previous award winners and the subjects of their lectures were:

- 1965, Leon Lapidus, Princeton University
"Aspects of Modern Control Theory and Application"
- 1964, C. R. Wilke, University of California (Berkeley)
"Mass Transfer in Turbulent Flow"
- 1963, A. B. Metzner, University of Delaware
"Non-Newtonian Fluids"

Changing Attitudes

TO REACTOR DESIGN

Octave Levenspiel

Professor of Chemical Engineering
Illinois Institute of Technology, Chicago, Illinois

Exciting things are happening today in the field loosely covered by the terms *chemical technology*, *reactor design*, and *kinetics*, for, without fanfare, study reports, or discussion in ASEE or in AIChE, a new way of looking at this subject was recently introduced. The new view may be characterized by the phrase *Chemical Reaction Engineering*, and its friendly reception by the profession is causing a remarkable change in our approach to and our teaching of chemical technology.

I should like to discuss this new development, to sketch its strategy as opposed to the traditional approach, to give a few examples to illustrate what I mean, to show how it has affected our pattern of education, and finally to consider what I feel is its place in the main line evolution of our profession.

In the traditional approach, we engineers were more concerned with the peculiar and

unique features of this or that reacting system than with the similarities and common characteristics among such systems. It is true that the unique features make for the success of a particular process. It is also true that what is useful for the processes of tomorrow are the analogies and generalizations which we are able to extract from the technology of today. Thus for predictive and design purposes we need generalizations; in the past, however, we have emphasized the particular and the unique.

In the U.S. of the forties we saw the first break with this philosophy. The general approach was brought forward; however, it was soon channelled, narrowed, and dominated by the problems and interests of the oil industry. Hence there was an overwhelming emphasis on catalytic reactions and a rather unhealthy preoccupation with developing models to account for their kinetics. Little wonder that this subject was known and is still known as *applied kinetics*, *chemical engineering kinetics*, or just *kinetics*, despite the fact that finding

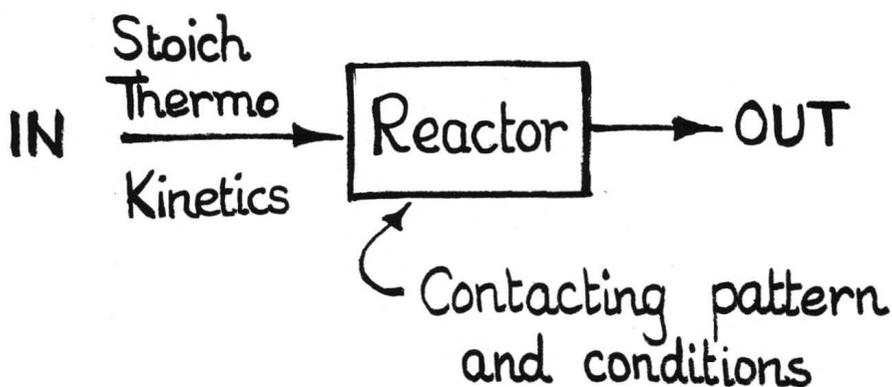


Fig. 1 — Schematic of Chemical Reactor Engineering

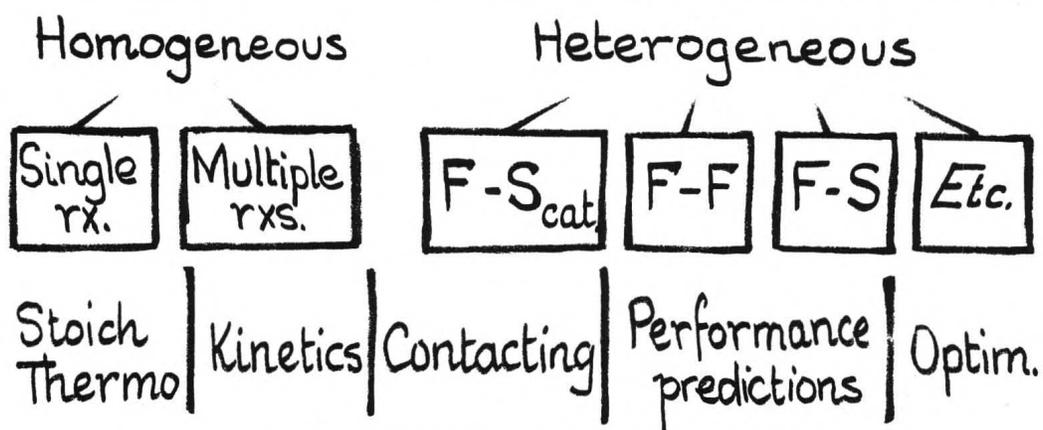


Fig. 2 — Classification of Reacting Systems

the rate of reaction is only one phase in the over-all problem of scale-up and proper reactor design.

In the late fifties a bolder attempt at generalization was started in Europe. To emphasize its concern with the over-all problem it was termed *Chemical Reaction Engineering* or CRE for short. As the name suggests, we are here concerned with the "engineering" of chemical reactions, or their efficient exploitation. The philosophy, then, is to seek common factors to link processes and to develop broad methods of attack for problems, and this is done with the conviction that these methods can be used as a basis for design in *all* areas of application, whether it be in polymer processing, industrial metallurgy, pharmaceutical manufacture, foods, biological processes, high-temperature reactions, or any other operation — in fact wherever a new material or chemical species is to be produced economically on a commercial scale.

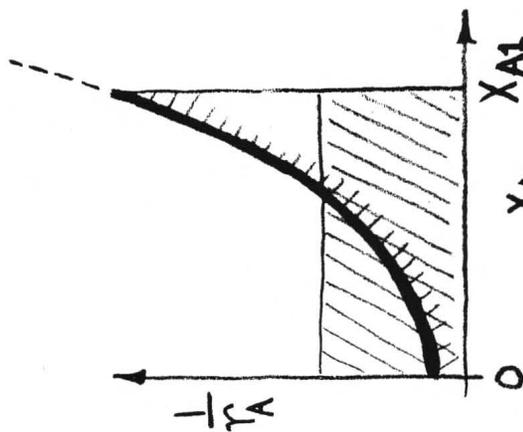
In a nutshell the concern of CRE is shown in Figure 1. Thus we engineers must determine how to treat a feed stream so as to obtain most economically a most desirable product stream. More specifically we must decide what temperature, pressure, and contacting pattern to use, and in general this decision requires knowledge of the stoichiometry, thermodynamics and kinetics of the systems.

It is convenient to classify reacting systems according to the phases participating in the reaction. As shown in Figure 2 the broad division is between homogeneous and heterogeneous systems. In the former, one fluid phase alone moves through the reactor

and only chemical kinetic factors influence the rate. In the latter classification, we may have to deal with additional problems arising as a direct consequence of the heterogeneity of the system, such as phase equilibrium, mass transfer from phase to phase or from phase to interface, and contacting pattern of the phases. As may be expected, heterogeneous systems represent a more complex situation.

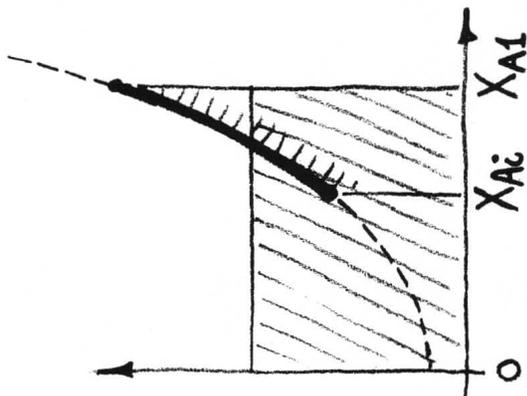
Next we see that homogeneous systems may be divided into systems where only one reaction occurs and into systems where two or more reactions occur simultaneously. The reason for this split is that different questions are pertinent in these two situations. With one reaction all we ask is to maximize conversion with a most economical reactor arrangement; with multiple reactions we ask how (by what temperature, pressure, and contacting pattern) to promote the formation of the desired product and depress the formation of all other undesired materials. The primary concern is not the same in the two cases. And so it is with heterogeneous systems, where we have (in what I consider to be the order of complexity) solid-catalyzed gas-phase reactions, non-catalyzed fluid-solid reactions (reduction of metal oxides, burning of coal), fluid-fluid systems (absorption with reaction), and finally the catch-all *et cetera* classification which includes all other multiphase systems. These systems can be horribly messy to treat, and in the interest of simplicity I shall avoid them in this paper, even though they include many processes of great industrial importance.

Plug Flow



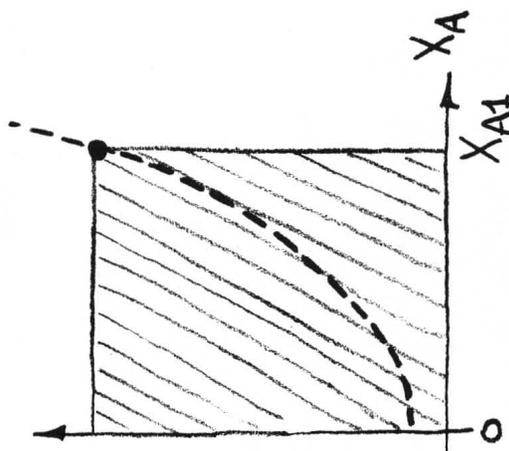
$$\frac{V}{F_{A0}} = \int_0^{X_{A1}} \frac{dX_A}{\tau_A}$$

Recycle



$$\frac{V}{F_{A0}} = (m+1) \int_{X_{A1}}^{X_{A1}} \frac{dX_A}{\tau_A}$$

Backmix



$$\frac{V}{F_{A0}} = \frac{X_{A1}}{\tau_{A1}}$$

Fig. 3 — Reactor Flow Patterns: Design Equations

The line at the bottom of Figure 2 shows the usual stages in our control of reacting systems all the way from initial studies on thermodynamics and stoichiometry to a search for optimum operation.

Our ability to handle problems is quite different in the different classifications. For example in homogeneous single-reaction systems we are at the stage of selecting optimum set-ups. In catalytic systems we would be just about as far along if it were not for the obstinate problem of representing and properly accounting for the kinetics of the reaction. With fluid-fluid systems our difficulties are everywhere: how to represent the rate usefully, how to account for movement of reacting species in the flowing phases, and in general how to predict the extent of reaction given all kinetic and equilibrium information. This means that except for special cases we have trouble trying to develop a design equation for this classification. And so it is with the other classifications shown in Figure 2; in each there are particular difficulties to be overcome.

Let me next offer three examples of recent research activities in CRE. They must be brief for this review to conform to rea-

sonable length. Nevertheless I hope that they will provide a feeling for the sort of thing that is going on.

The first example concerns the search for an optimum set-up for the single catalytic reaction whose thermodynamics and stoichiometry are known, and let us restrict ourselves to adiabatic operations in packed beds. Now there are many possible ways of running such a reaction — for example, single-stage operations in one packed bed reactor, multistage packed-bed operations with interstage heat transfer, operations with recycle of fluid between stages or with bypassing of certain stages with fresh feed. And for every set-up we can choose the temperature of fluid entering the various stages. With all these factors at our control, are we to make a computer search of every possibility that comes to mind, or are there methods which give us a feel for the situation and allow us to reject quickly many of the alternatives while retaining those few which are promising? Since I favor the latter approach let me outline a graphical method which does just that.

Figure 3 shows the design equations for the flow patterns of interest: the ideals of plug flow and backmix flow and the inter-

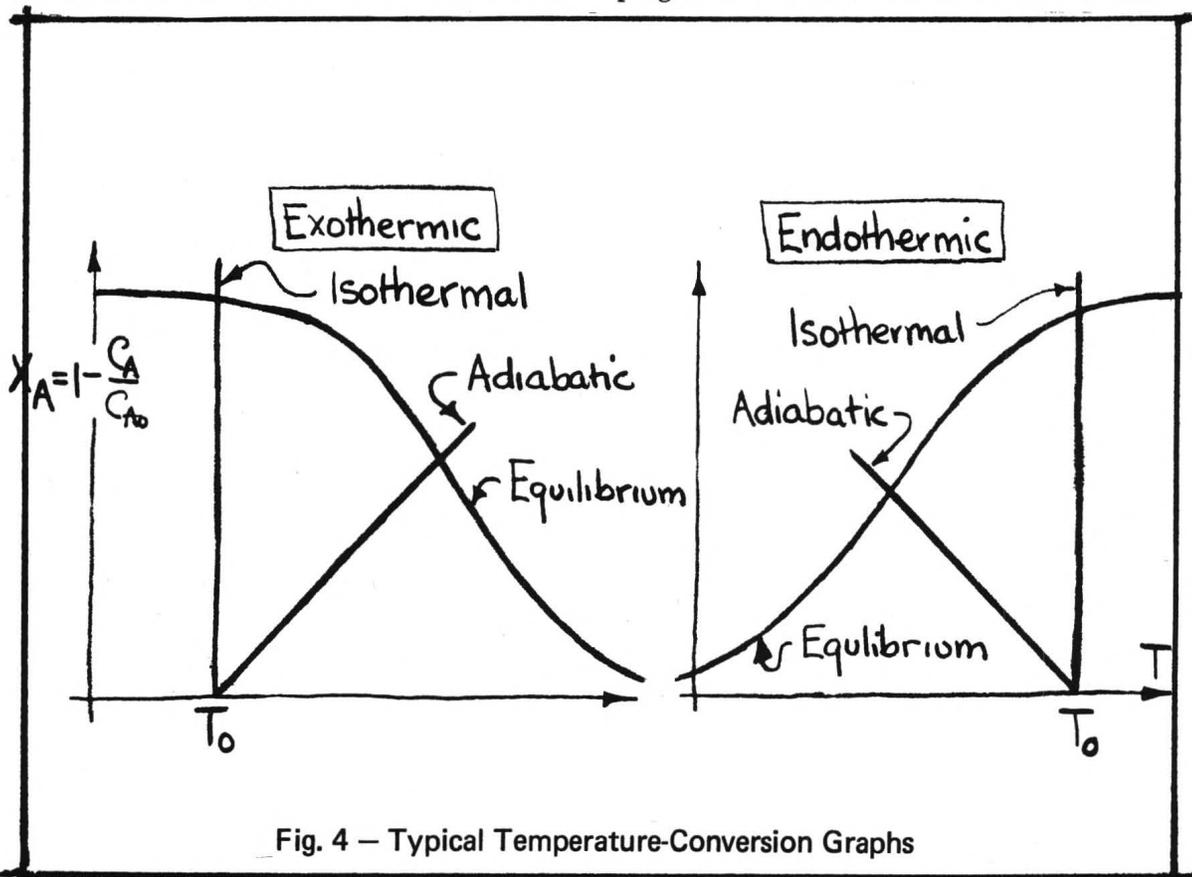


Fig. 4 — Typical Temperature-Conversion Graphs

mediate of recycle flow. It should be noted that plug and backmix flows represent the extremes of recycle flow when the recycle ratio m becomes zero and infinite, respectively. These equations indicate that the four quantities, V (size of reactor), F_{A0} (feed rate of reactant A), $-r_A$ (rate of reaction), and X_A (conversion of reaction)

are all interrelated, and knowing any three of these quantities gives the fourth. The sketches in Figure 3 are a graphical representation of these equations for any arbitrary kinetics and the shaded areas are a measure of the size of reactor needed for a given duty. These expressions are quite basic to CRE.

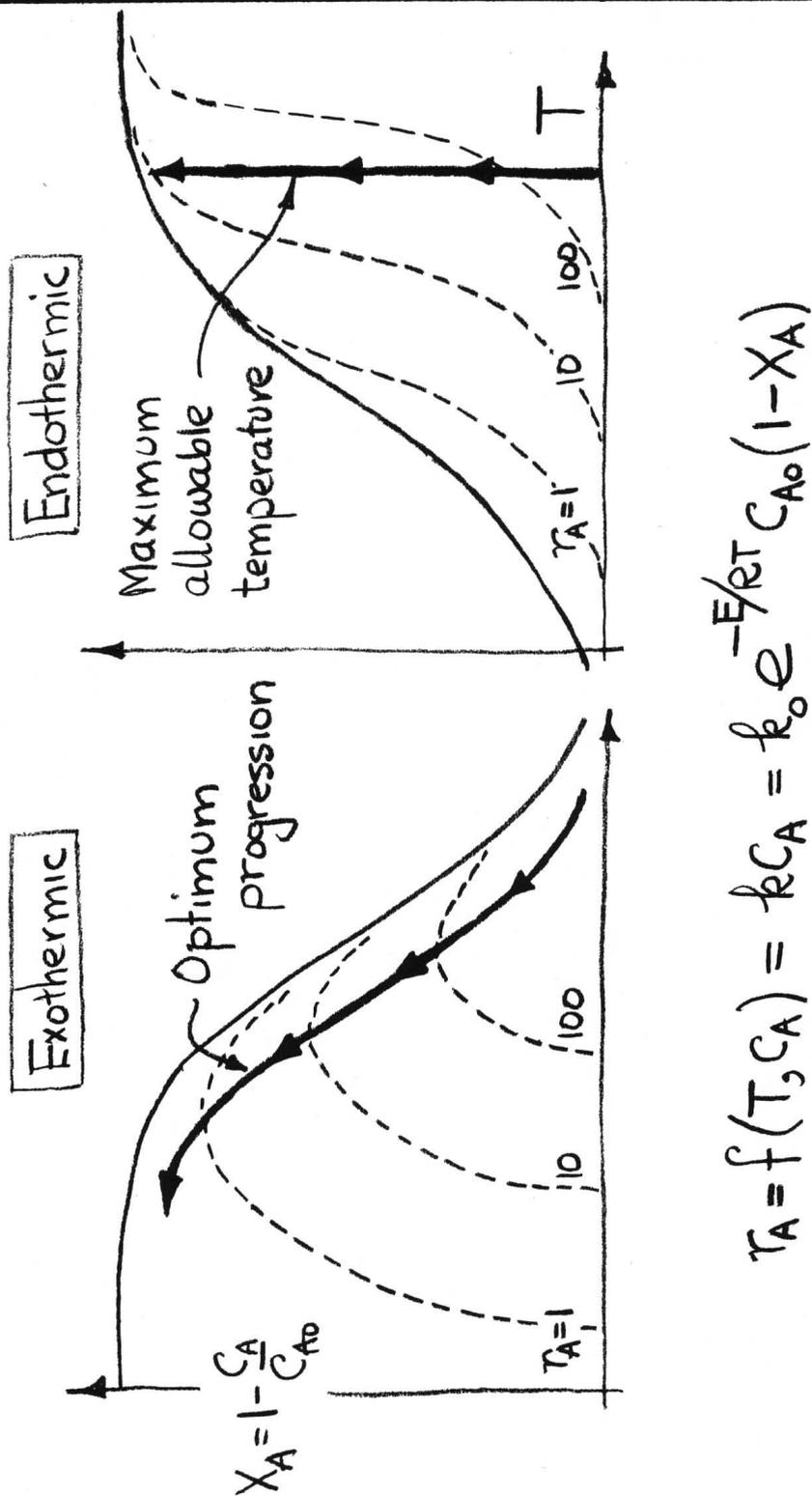


Fig. 5 — Optimum Temperature Programming

Figure 4 is the temperature-conversion graph for typical exothermic and endothermic reactions when starting with a given feed. Shown in this figure are the equilibrium curves obtained from thermodynamic considerations and typical reaction paths starting with feed at temperature T_0 , both for isothermal and adiabatic operations. In the succeeding figures we

shall build on this plot. I shall discuss only the exothermic situation, but I include in the figures the corresponding endothermic reaction for the reader who wishes to pursue that case on his own. The logic of the two situations is somewhat similar.

Now to Figure 5: the dotted lines show the locus of constant reaction rate, and this general shape again is typical of all re-

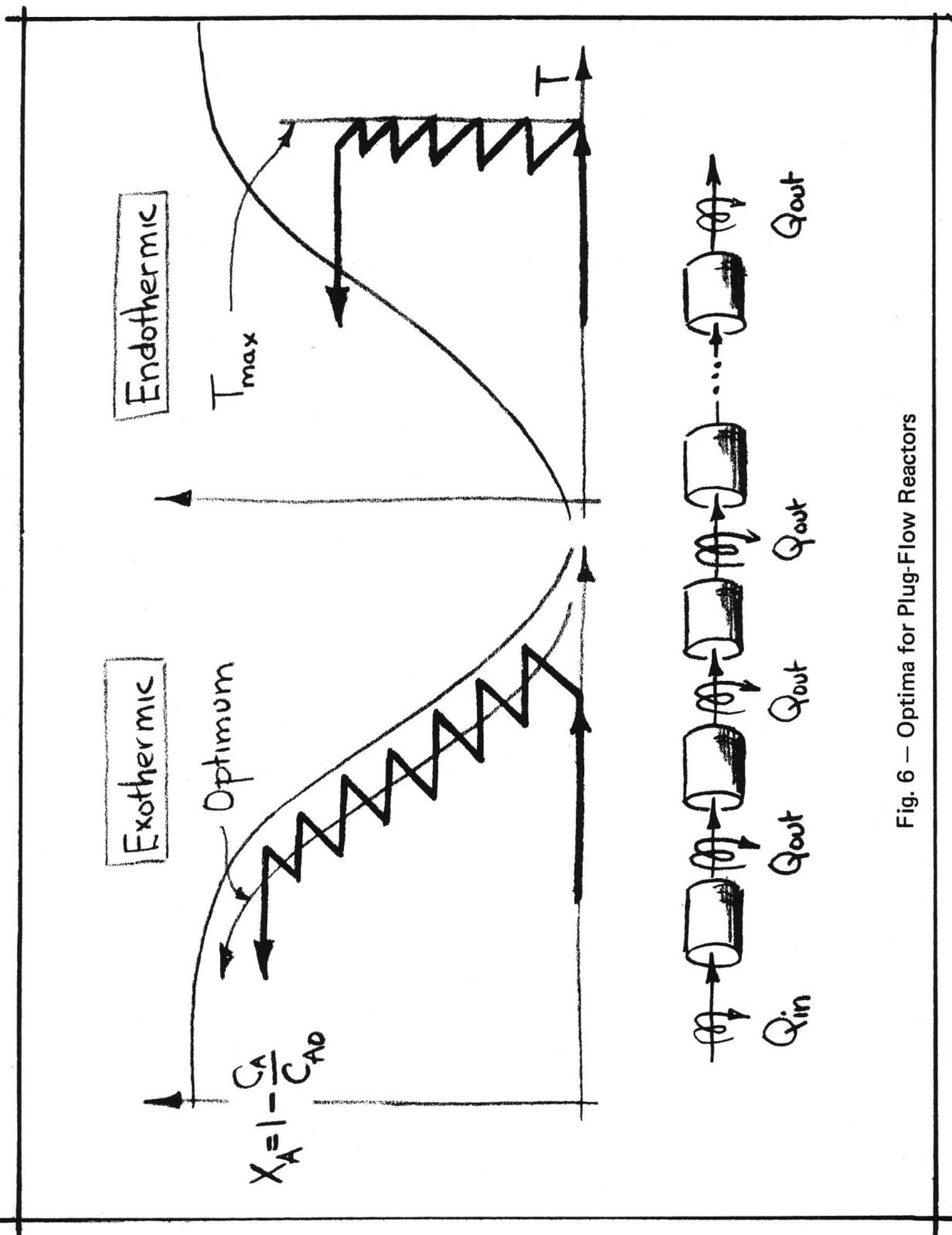


Fig. 6 — Optima for Plug-Flow Reactors

actions. Next, to minimize the size of reactor we want to choose the temperature where the rate is maximum for that composition. The heavy line in this figure shows the progression of temperatures which satisfy this condition. Comparing with Figure 4 we see that the slope of this optimum line is opposite that for adiabatic operations.

Because of the opposite slopes the way

to approach this optimum with plug flow units is shown in Figure 6. Abiatic stages with intercooling are required. It is apparent that intercooling simply shifts the operating line horizontally to the left on this graph.

Since it is impractical to use a large number of stages, we may start by examining one-stage, two-stage, and then three-stage operations. Figure 7 illustrates how

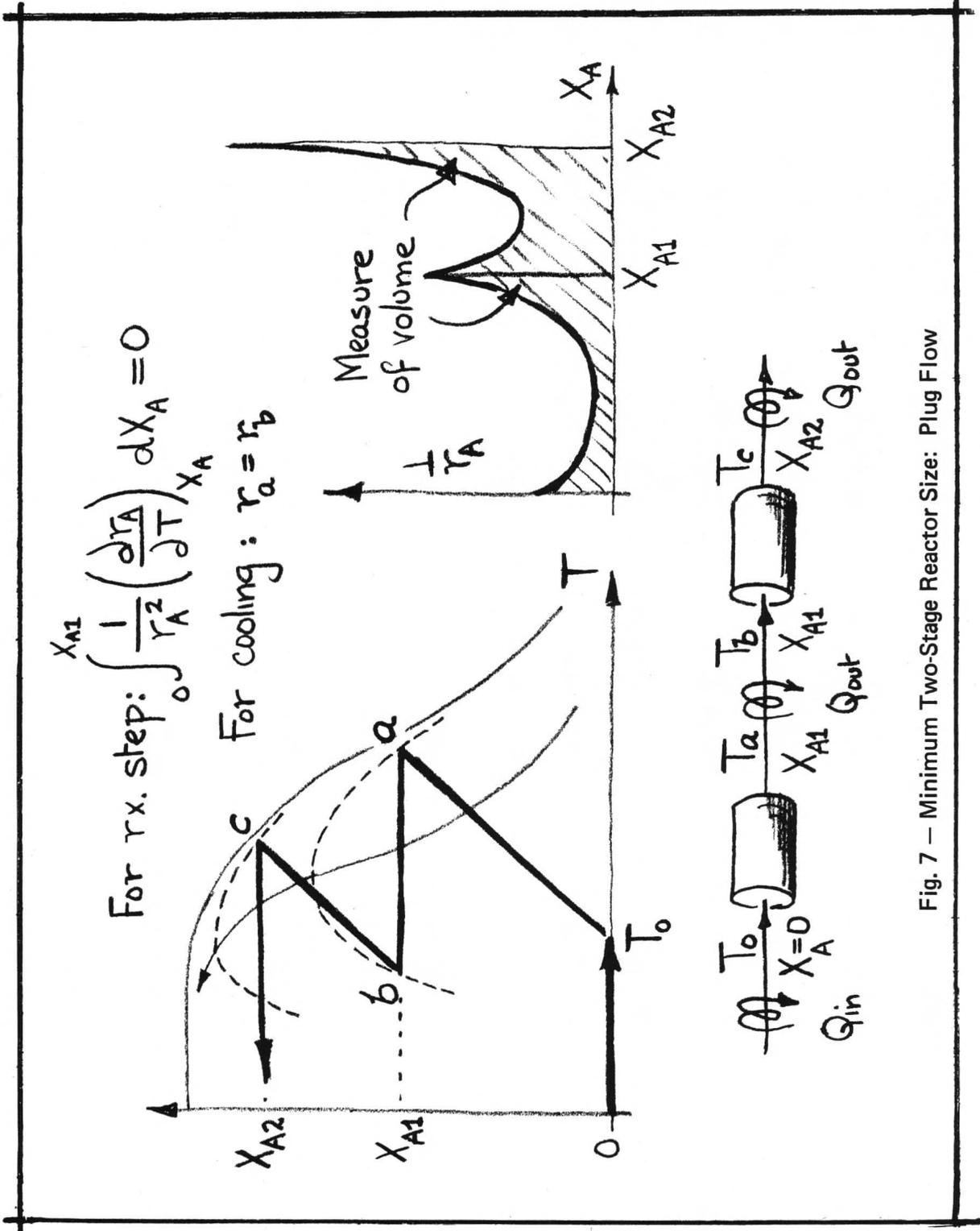


Fig. 7 — Minimum Two-Stage Reactor Size: Plug Flow

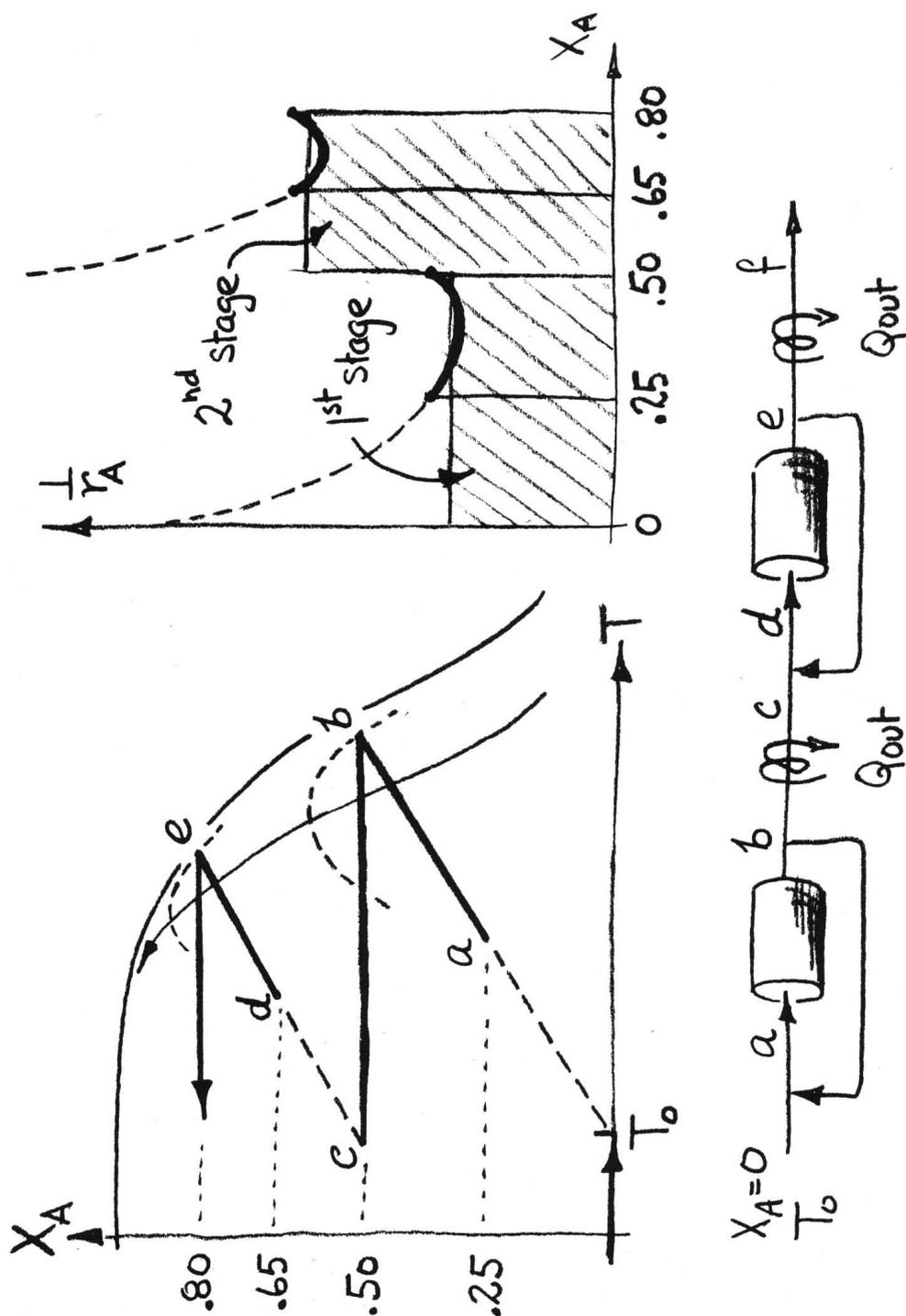


Fig. 8 — Minimum Two-Stage Reactor Size: Recycle

to find the minimum size of a two-stage plug-flow unit to achieve a given conversion X_{A_2} . The procedure is a one dimensional trial-and-error where T_0 alone is guessed. Points a and c are found by the integral given in the figure and point b has the same rate as point a . Figures 8 and 9 sketch analogous plots for recycle and for backmix flow.

Again we ask if we must search all these

possibilities. Figure 10 indicates that this is not necessary and that the key to the proper contacting is given by the slope of the adiabatic operating line. For the shallow slope of case a the rate of reaction is extremely low at low conversions; hence we should avoid operating in this range of conditions. This immediately suggests that we use backmix flow or recycle flow with a high

(continued on page 64)

About—The Industry-University Interface

The classical conception of an interface, bounded by several high resistance films and across which mass and energy are transported under the influence of a driving force, has undoubtedly been of more value in the solution of real problems than any other concept one could name. Engineers have always been singularly perceptive, if not ruthless, in the adaptation of engineering terminology to the description of human behavior. It is not surprising then, to find "interface" being used in a particularly appropriate sense to describe the transfer of intellectual capacity between groups which have quite different responsibilities and interests. No empty verbalism this, for the use carries with it the connotation that a resistance to the transfer process does in fact exist.

I have returned to the academic cloister from a most interesting and exciting sabbatic leave during the 1965-66 academic year as a full-time engineering consultant in the Engineering Technology and Services Branch of Monsanto's new Central Engineering Department. I functioned during the entire period directly with Monsanto professionals in the solution of short-term problems and in the development of new technology for long-term application. I now can see the process industry-engineering college interface in detail. The resistance on the industrial side is minimal, but it is certain that the academic side resistance is much too high for the single reason that there appears to be much more concern in the engineering colleges with advancing science than with making the advances of science useful. Clearly, there has been serious abrogation of responsibility by the colleges in the teaching of analysis, synthesis, and design to meet modern day demands — both at the undergraduate and more seriously, at the Ph.D. level.

In the broad spectrum of engineering activity, research has rightly been the pivot between practice and theory. Massive infusion of the colleges with government contract research funds over a period of several academic generations has brought us to the point where the design naivete of the instructor is producing students who are design deprivates. Undergraduate students, in general, are not being properly prepared to cope with the very real and extremely complex engineering design problems of today, and if the present trend toward greater acceptance of the non-experimental or "paper" thesis continues, the engineering Ph.D. degree is in danger of becoming an anachronism. Development of acceptable design competence in the student is an enormously difficult task in comparison to the development of research and theoretical competence. Even if the engineering professor did not exist in a design

Immediately upon receipt of the B.Ch.E. degree from Rensselaer, Raymond G. Thorpe was ordered to active duty in the U. S. Navy and served for four wartime years. After the war had ended and he had received his discharge, he pursued and earned the M.Ch.E. degree at Cornell. He joined Monsanto's Plastics Division, but ultimately was drawn back to Cornell where he has remained for over ten years.

A year of academic leave spent consulting with Monsanto's Central Engineering Department crystallized thoughts about the relationship between engineering academe and industry that Professor Thorpe had been forming for some years. His observations were first published in the *Monsanto Technical Review*, whose permission to reprint them here CHEM ENG ED gratefully acknowledges.

and technology void, the task would still be difficult — and expensive. The industrial sabbatic leave is one mechanism by which the engineering professor may, it would seem, acquire the necessary insight and skill for design teaching. All too often, however, the young engineering professor is merely transplanted from his own limited academic research surroundings to a broad-based industrial research environment. He gains in research experience, fulfills both his academic and industrial objectives, and returns to the campus. His research-conscious academic administrators are satisfied, but his students continue to remain design cripples.

Monsanto engineering management believes that technological upgrading of the young engineering professor is not only necessary, but possible. What is required is that the professor be temporarily absorbed into an engineering organization and permitted to function as a permanent employee without restriction. Monsanto does not subscribe to the concept of the prolonged guided tour, but feels that mutual maximum benefit can only occur if complete professional interaction takes place in a climate in which the professor is not only permitted free access to company personnel and technology, but most importantly he is exposed to real economics and encouraged to make a genuine contribution in decision making processes. It is assumed that the professor, from a new vantage point comparable to that of the process designer, may reach certain inescapable conclusions with regard to the limitation of the purely theoretical approach and the true worth

(continued on page 69)

(continued from page 62)

recycle rate. On the other hand plug flow is quite satisfactory for the steep slope of case *b*. The numerical values shown on this slide represent a heat of reaction of 30 Kcal. So, simply by making this type of graph we can tell what class of contacting schemes to examine and what class to reject.

Other alternative arrangements can also be considered, for example the cold-shot cooling of Figure 11. This arrangement

eliminates all the interstage heat exchangers; however it is only practical to use this scheme under the conditions shown in the figure.

Only a detailed cost study of exchangers, catalyst, pumping, and the like will tell which set-up is best in a specific situation; however, I like this graphical procedure because it is rapid and simple to use, it is general, and it is easily extended to non-adiabatic and to homogeneous reactions. It

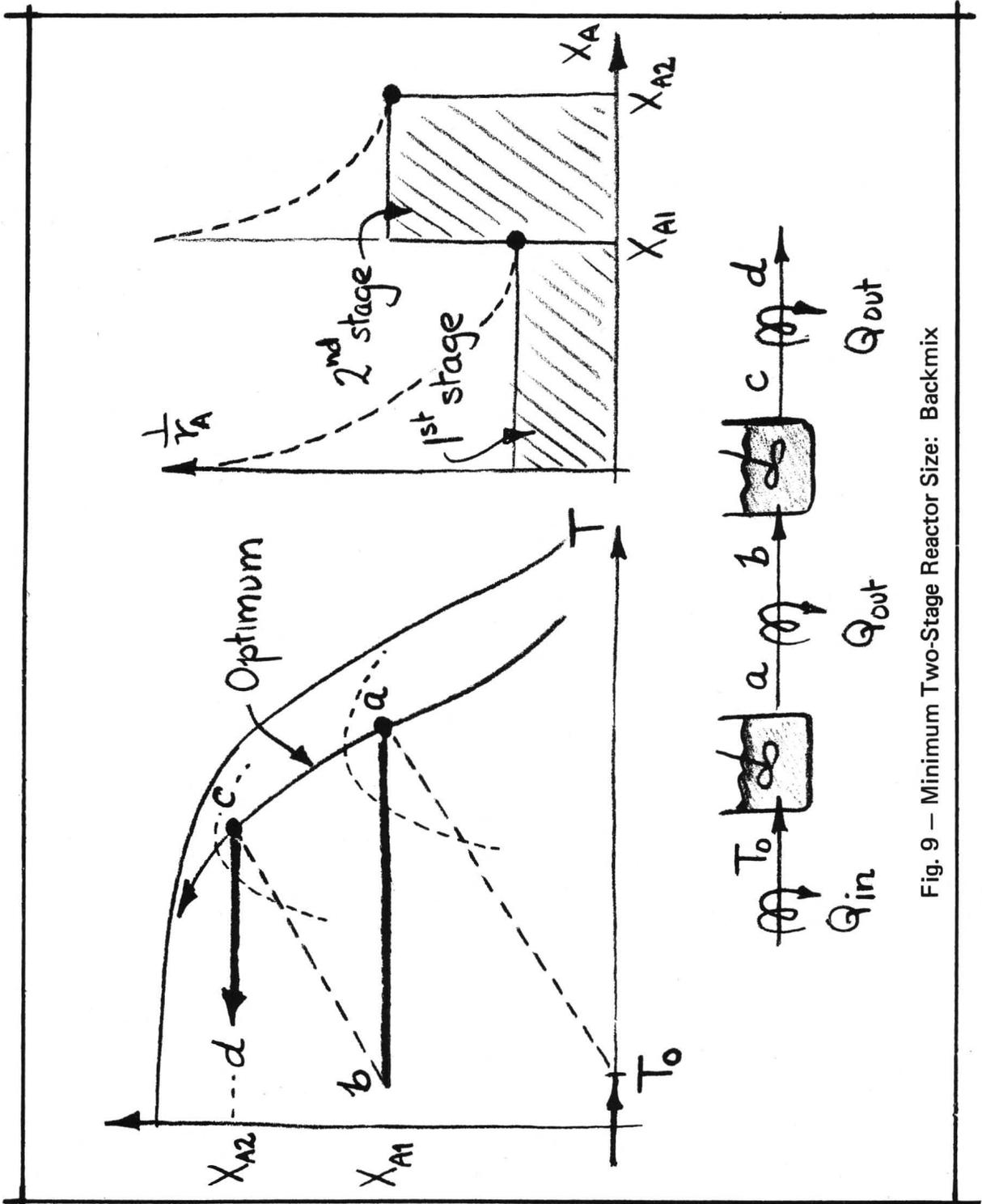


Fig. 9 — Minimum Two-Stage Reactor Size: Backmix

also gives a visualization, a feel, for what is going on. I can't help thinking that its role in reactor design is somewhat like that of the McCabe-Thiele method in distillation.

But enough. Let us look at another area where a search for generalizations is going on. This concerns multiple reactions and the question of product distribution.

Suppose we have a feed consisting of the

two dichloro compounds shown on the left side of Figure 12 and we want to know how to contact this stream with chlorine so as to maximize the formation of the desired trichloro compound. Should we use counter-current contacting, concurrent contacting, a vigorously agitated vat through which chlorine is bubbled, or some other arrangement? The direct way of answering this question is to evaluate the five rate con-

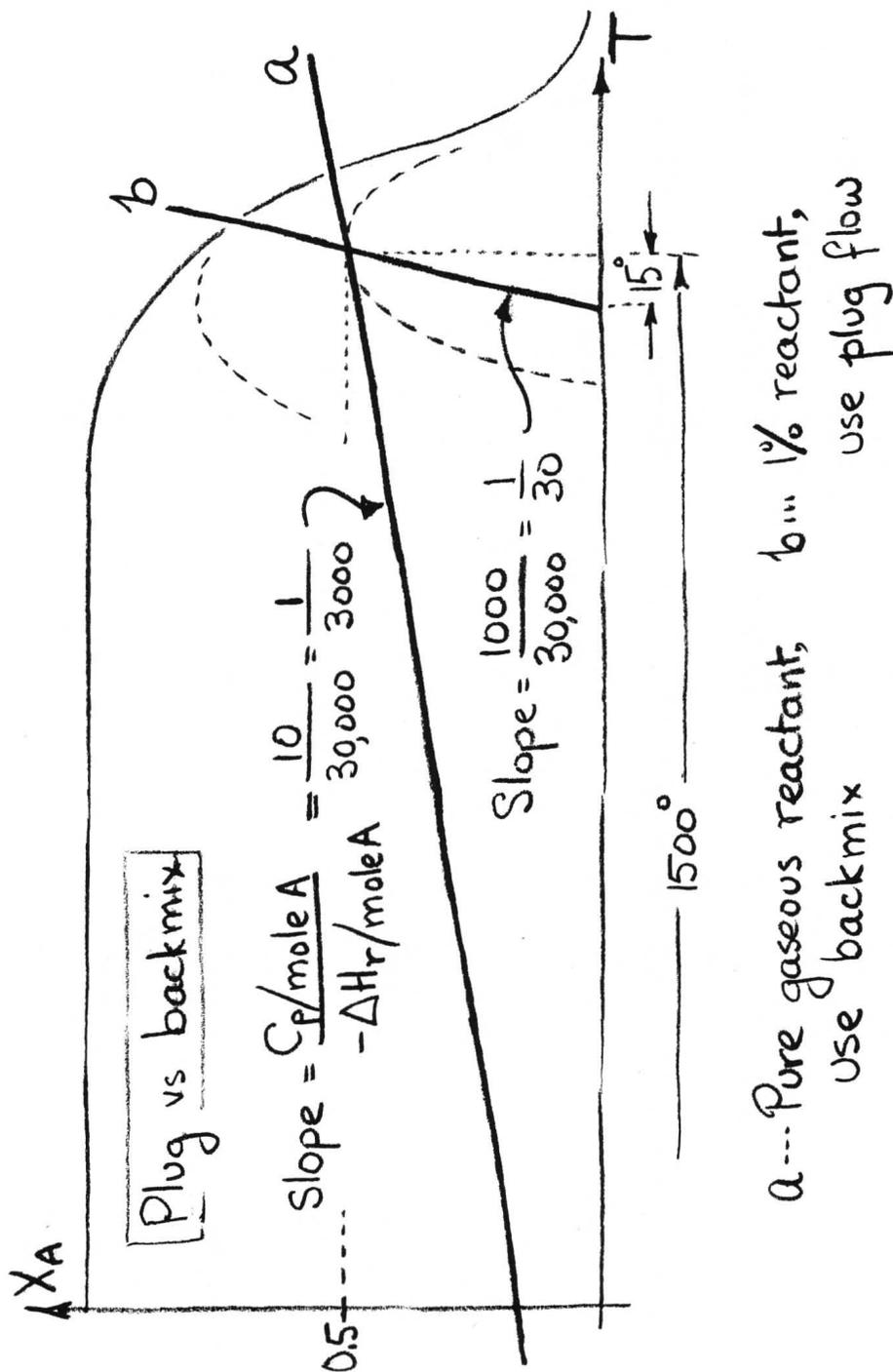


Fig. 10 — Adiabatic Operating Lines

stants and then to solve the design equations for the various contacting patterns. It would be very nice, however, if we had some general rules allowing us to find the best contacting pattern, not only for the reaction shown in Figure 12 but for other reactions as well, without going through the detailed calculations, or better still, without even

knowing the values of the rate constants. Such rules would be a useful guide and a great timesaver.

A number of such rules have indeed been proposed to date. Some have been proved, while others are still conjectures. Let me present a few of them.

Rule 1. For reactions in parallel, for ex-

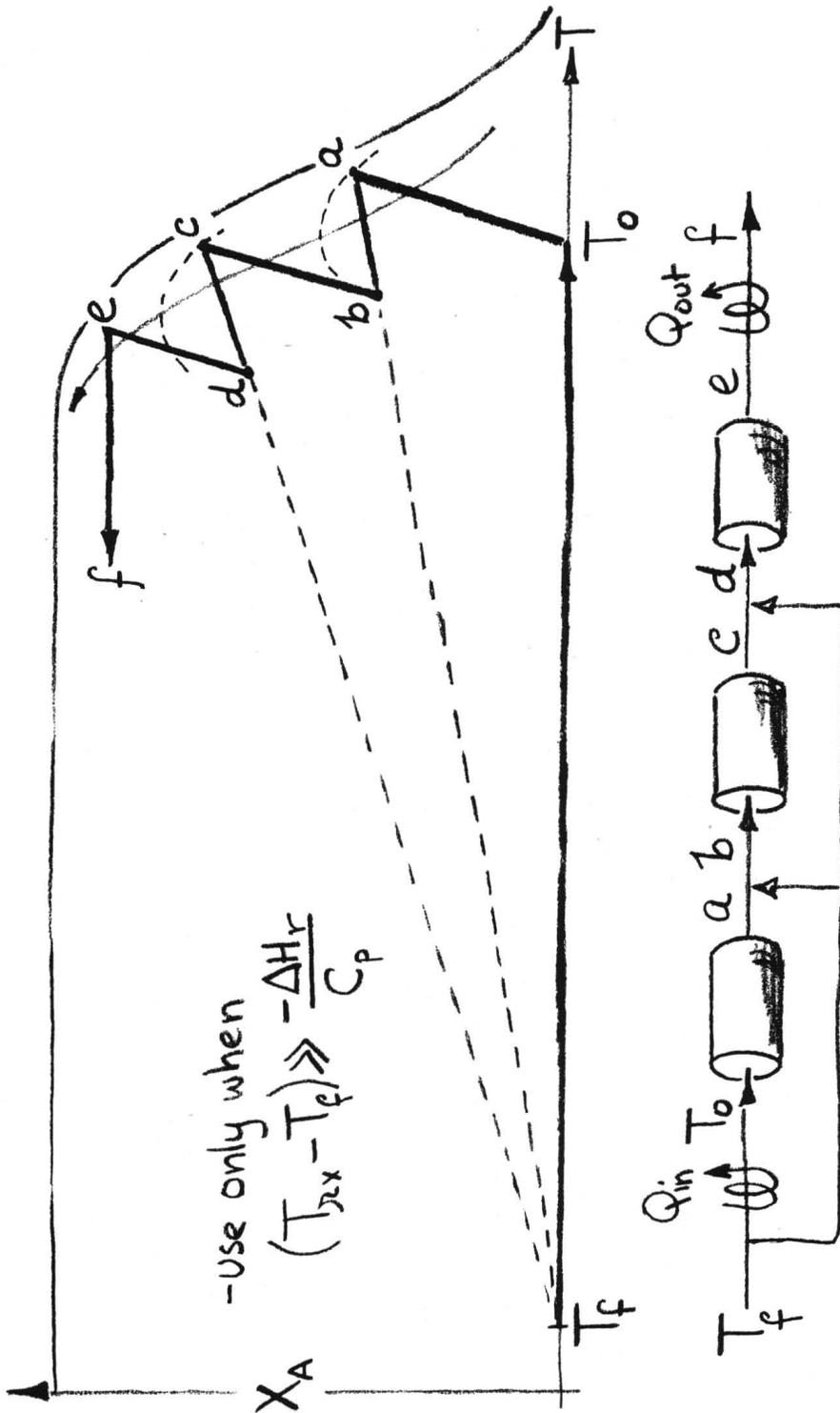


Fig. 11 — Cold-Shot Cooling

ample $A \begin{matrix} \leftarrow R \\ \leftarrow S \end{matrix}$, the concentration level of materials is the key to proper control of product distribution: a high concentration of a component favors the reaction of higher order with respect to that component, a low concentration favors the reaction of lower order.

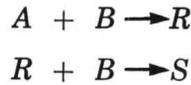
This rule is easy to prove for parallel reactions of all kinds including catalytic and autocatalytic.

Rule 2. For reactions in series, say $A \rightarrow R \rightarrow S \rightarrow T$, keeping the composition homogeneous, thus not allowing material of different composition to mix, will allow a maximum amount of any intermediate to be formed.

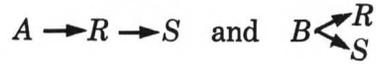
This rule has also been proved in general for any stoichiometry and reaction kinetics and for any intermediate in the reacting chain.

Rule 3. Multiple reactions can be looked upon as a combination of their constitu-

ent series and parallel reactions, as far as product distribution is concerned. For example, the consecutive competitive reaction scheme



can be looked upon as the sum of



This rule is useful and allows us to break down complex reaction schemes into their building blocks, from which the optimum contacting pattern can easily be found.

Rule 4. With respect to product distribution every non-continuous contacting set-up has its steady-state continuous-flow analog and vice versa.

This rule suggests, for example, that if you can produce a polymer with a specific molecular weight distribution in batch operations then you should be able to design a

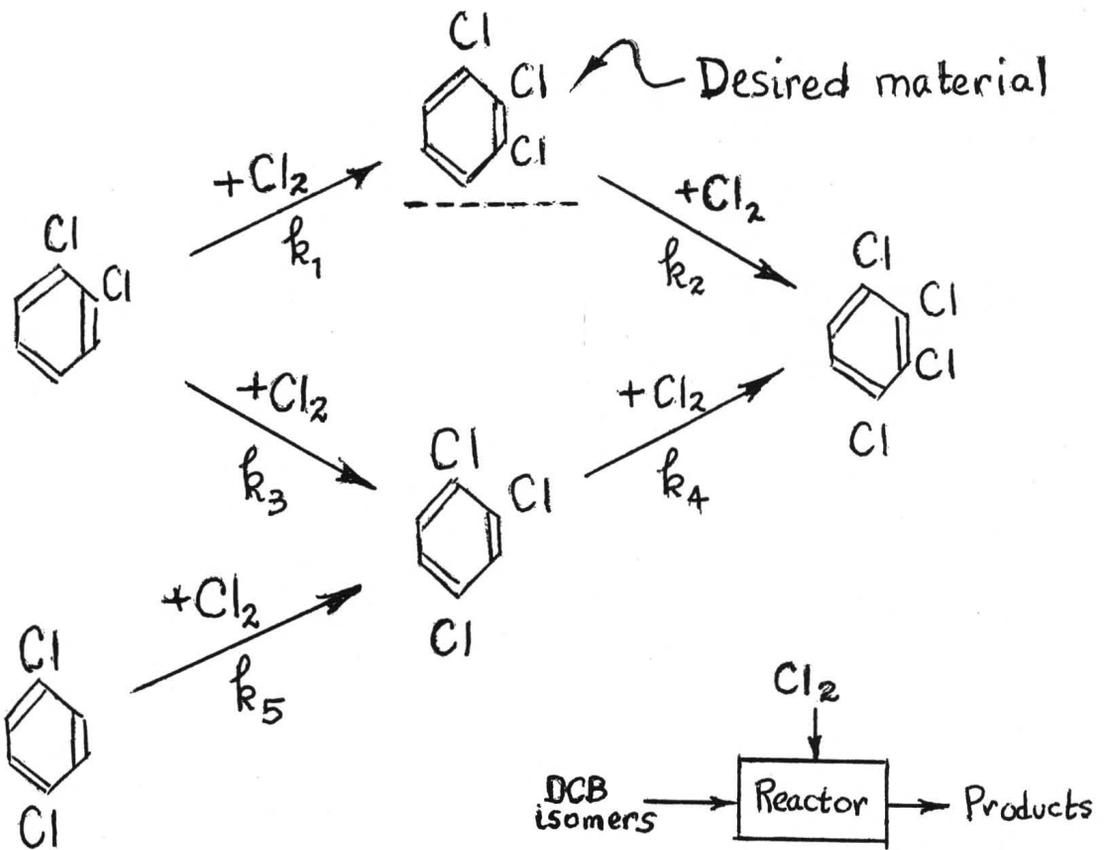
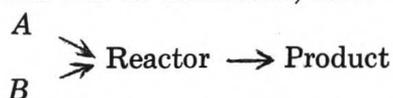


Fig. 12 - Multiple-Reaction System

continuous process which will give the same quality product. Also beer, traditionally batch-prepared, should be produceable continuously*. I suggest this rule with some hesitation because it has occasioned rather antagonistic responses, with counterexamples quoted from the literature. In fact, none of the counterexamples have held up. Thus, the rule is still open to question — it has yet to be proved or disproved.

Rule 5. For a given set of reactions, optimum contacting is independent of the value of the rate constants.

This rule certainly holds for some of the simpler reaction schemes, such as those indicated in Rules 1, 2, and 3. It can be shown by counterexample, however, that it does not hold for all reaction schemes. My opinion is that it holds if reactants enter in separate feed streams and if their introduction can be controlled, thus



but that it does not hold if the reactants enter or are present in the reactor in a fixed ratio which we are not able to control, say if they enter in one stream



Rule 6. The steady-state optimum can never be surpassed by unsteady-state operations.

This is an interesting rule because recently a number of papers have appeared suggesting that unsteady state operations can raise conversions and improve product distribution. All right then, in terms of general classes of reacting systems what are the limitations to this rule? Is it applicable to homogeneous systems? To those with mass-transfer-controlled kinetics? This is what we need to know.

I could suggest others, but I think that these six are enough to indicate the sort of thing we are looking for. Actually we are just beginning timidly to probe this area, uncertain even of the questions to be asked, never mind the answers. What we need is our own modern day Euclid for this area of CRE.

The examples cited have been intended to demonstrate that the concern and emphasis in CRE is quite different from the

*It is being so produced. Ed.

approaches used in the past. Also, with all the discussion in educational circles about what constitutes proper research, I cannot escape the conclusion that this type of activity, this search for generality which is useful for design and prediction, is indeed *engineering research* in the proper sense of the term.

Now to engineering education: here we must ask how best to prepare students for prediction and design for the problems of tomorrow. Well, the basis of all experience has shown that generalizations and universals are our best bet, not the details and particulars of this or that phenomenon or process. Generalizations constitute teachable knowledge, whereas the teaching of facts that stand alone and outside of any general conceptual framework is simply the passing on of today's art. In fact, I may go as far as to say that until a general point of view is taken a subject cannot be taught effectively.

To show that CRE does constitute such teachable knowledge let us see what happened to the educational pattern after CRE appeared on the scene. First of all the first congress on CRE, where its program was first spelled out, was held in 1957. The 1962 ASEE survey of under-graduate chemical engineering education in the US gave these figures:

In 1957 18.5% of schools taught "Kinetics"

In 1961 53.2% of schools taught "Kinetics"

Professor Thatcher, who prepared this report, considered this large jump to be the most significant shift in the chemical engineering curriculum in this period. Why the increase? Is it a coincidence that not long after the CRE approach was introduced this subject — which had always been important — all of a sudden became teachable? I'm convinced that it is no coincidence. And if you compare the subject matter — before and after — in these courses I'm confident that you too will say that the CRE approach was largely responsible for this shift.

As of today my guess is that the 53% figure has risen to over 80%. This is a remarkable development especially in view of the fact, as I mentioned earlier, that it has taken place without major discussion in ASEE or AIChE.

Finally I'd like to say a few words about CRE and the main line evolution of the profession. Early in this century the unit operations approach was the unifying principle which brought order to the study of the physical operations of chemical technology, and it became the focal point about which chemical engineering as a profession achieved its identity, flourished, and grew. Now, fifty years later, in the midst of much

questioning in the profession about identity and purpose, I see the promise of a similar but broader unification, this time encompassing the chemical operations and with CRE as its vehicle. Such is the role in our ever-changing profession which I envision for CRE, an approach whose name and program were clearly spelled out a short nine years ago. Only time will tell whether we will shape CRE to fulfill this promise.

Octave Levenspiel was born in 1926 in Shanghai, China, and grew to manhood there. He came to the United States in 1946, became a citizen in 1958, is now married and has three children.



He attended a German elementary school, British secondary school and French University (Universite l'Aurore) all in Shanghai. Dr. Levenspiel received his B.S. degree in chemistry in 1947 from the University of California at Berkeley and his M.S. and Ph.D. degrees in chemical engineering in 1949 and 1952 from Oregon State University.

Except for one year in research at University of California (1951-52), Dr. Levenspiel has been continuously in engineering education. He taught at Oregon State University (1952-54), Bucknell University

(1954-58) and Illinois Institute of Technology (1958 to the present), where he is now Professor of Chemical Engineering. In 1963-64 he spent a year at Cambridge University as a National Science Foundation Senior Post-doctoral Fellow.

In research and scholarly activities his interests have centered about the use of knowledge and the development of the general approach for prediction and design. In this line he has published articles on heat transfer, fluidization, the design of chemical reactors and flow patterns of fluids in vessels. He has written a review on the last named subject in "Advances in Chemical Engineering", Vol. IV. In 1962 he wrote "Chemical Reaction Engineering" to introduce students to the method of design of chemical reactors.

Dr. Levenspiel is a Professional Engineer (State of Oregon) and has strong interests in the philosophy and history of science, and in statistics.



(continued from page 63)

of his own academic research. The student will inherit a long overdue legacy if administration in the engineering colleges will recognize that the intangible non-research activity so necessary for analysis, synthesis, and design is not only academically legitimate, but important.

Many industrial managers hold the view that the market for highly theoretical and research trained engineering Ph.D.'s in narrow specialty areas is rapidly becoming saturated. Progressive graduate schools might very well either: 1, consider adoption of a requirement that a portion of the engineering doctoral candidates demon-

strate an acceptable degree of competence in design, or 2, adopt curricula which will produce broadly trained design professionals at the advanced degree level who are able to utilize modern computational facilities to the fullest extent. Training of our young people cannot be done by professors who are themselves design illiterates.

Solutions to the problem of design instruction will not fall out easily. We do, however, have an effective way of using a new dimension in industry-university cooperation to scaledown the problem.



THE CHEMICAL ENGINEERING

APPROACH TO ENTROPY

Views of A Non-Thermodynamicist

James L. Throne

Assistant Professor of Chemical Engineering
Ohio University, Athens, Ohio

In a recent article (2), Bates sets forth some "canonical statements" in an attempt to clarify some of the irrational concepts and misleading labels which have evolved with thermodynamics, probably beginning with Black and the concept of "calorics" (5). I wish to take issue not only with Bates' approach to the healing of thermodynamics, but with the entire philosophy of teaching thermodynamics on the undergraduate-first year graduate level. In this paper, I would like to present what might be called a "non-thermodynamicist" viewpoint to the problems of teaching thermodynamics, my focal point being the concept of entropy and its abuse in chemical engineering. In a subsequent paper, I intend to present a course outline for thermodynamics on, say, a first year graduate level in chemical engineering. Such a course has been taught successfully at Ohio University by non-thermodynamicists.

Forests and Trees

While Bates' arguments regarding misconceptions and irrational nomenclature are well taken, I am not convinced, first, that his introduction of another set of nomenclature (regardless of its rationality) is "first aid," and second, that even if adoption of a standard set of symbols, definitions, axioms, canonical statements, and what have you, *does* take place (highly improbable, when, for example, Tribus (1) introduces, through information theory, concepts such as "temper"), that this type of first aid will not result in direct application to thermodynamics of the old saw, "the operation was successful, but the patient died."

I think that the dying patient, which I prefer to call mechanical thermostatics (bowing to Tribus' careful definitions here), needs radical surgery, transfusions, and miracle drugs rather than simple first aid. Perhaps the time has come for the engineer who utilizes thermodynamics (in its true sense, i.e., transport of heat, mass, and momentum) in his work with physical and chemical phenomena (and here it must be understood that I am referring to a much greater scope of problems than those outlined by Bird, Stewart, and Lightfoot (3)) to render advice and, if necessary, to step in and perform the necessary surgery himself. It may well be that those who now apply first aid may see only single trees where entire forests (mostly unexplored) lie waiting.

Philosophy and Thermodynamic Concepts

As is well known, there are two major ways of approaching the developments of the major corner-stones of thermodynamics: through classical or macroscopic developments and through "statistical" or molecular developments. Both paths originate in physics and *both* require the person following the development to make some form of idealizing assumption. While I will have more to say on this point in the subsequent paper, I want to point out two recent important changes in emphasis, one in each approach. In classical thermodynamics, much work is being carried out in "moleculeless" continuum mechanical thermostatics. While we seldom use this title, the development of the energy equation explicitly depends upon this approach. In statistical thermodynamics, Tribus' work and that of others dealing with the development of a thermodynamics which relies on information theory alone must be considered as a novel way of developing the same principles one can obtain from "classical" (as opposed to quantum) statistical thermophysics.

Undergraduate chemical engineering thermodynamics courses are apparently so crowded now (too many trees?), that aside from isolated experimental attempts (1) to introduce statistical concepts, only the macroscopic approach is emphasized.

Since we are dealing here only with undergraduate thermodynamics, and since we must recognize that thermodynamics is truly a building block in the over-all concept of chemical engineering process and product design (or if you prefer, systems and materials engineering), the pragmatic philosophy must control the way in which we present the three laws of thermodynamics and their applications to real engineering problems.

Let me point out that, unlike Bates, I believe that the first law of thermodynamics is the "canonical statement" of temperature, the second, of energy, and the third, of entropy. My position, incidentally, places me directly in the path of cross-fire from the mechanicians who choose work and power for the second and third laws and the thermodynamicists who choose internal energy and reversibility. It is *not* true, in my opinion that the concept of entropy is more abstract than that of energy, which in turn, is more abstract than that of temperature. *All* concepts are abstract, if one follows the Platonic philosophy; as a result, if we are to use these concepts in any pragmatic (and hence, engineering) way, we must make approximations to them. The student thinks he knows what temperature is; he makes a "heat" balance and thus has some connection, on paper or by

relation to some physical process such as heat transfer, with the engineer's idea of conservation of energy. However, what makes entropy mysterious (and thus, to the student at least, "more abstract") is *not* the abstract concept, but our inability to measure it with a meter!

What Good is Entropy?

To this question I am tempted to answer "none," at least as entropy is presently taught to undergraduate chemical engineers. If we deal solely with the macroscopic mechanical thermodynamic developments, the classical development of the concept is through Kelvin refrigerators or Clausius (Carnot) heat engines, via the TS versus PV diagrams, to the second law relating a new variable, called entropy, to a measure of reversible heat and temperature. The next step is to rush into irreversible systems, to "prove" that entropy in any conservative system must either remain constant or increase with time. Siedel (6) at one time collected some 25 statements said to define entropy. At this point, reinforcement of the concept is needed (again because we can't measure entropy) and in desperation and with trepidation, the thermodynamicist dips into statistical thermodynamics and extracts the statement that entropy is a measure of the disorder of the system. Thereby he escapes cross-examination either because the student is too confused to ask for clarification or because no real use is made of the pseudo-concept anyway. Now I wish to raise two questions:

1. Why, if statistical thermodynamics is to be referred to at all, must it be emasculated *only* to support an archaic approach to the ideas of teaching entropy?

2. Why is it necessary to teach *mechanical* thermostatics to chemical engineers at all? Carnot engines and Kelvin refrigerators are great devices for making simple heat balances, but certainly more realistic examples like fuel cells, air liquefaction, and fresh water recovery are more vital. The tired answer to this is, of course, that the subject has been presented this way for years, so why rock the boat?

Boat-rocking notwithstanding, I would now propose the pragmatic approach to the concept of entropy, leaning heavily on the recent work of Coleman (4). Rather than 1) wasting time and increasing confusion by introducing statistical thermodynamics and 2) spinning wheels playing with cycles and reversibility-irreversibility, I suggest that the engineer's approximation to the concept of entropy be put to work. From classical thermodynamics we can determine whether a process is reversible or irreversible, but we have no idea of the rate at which a process is approaching an equilibrium state (if ever), or the rate at which conservative (reversible) energy is being converted into dissipative (irreversible) energy. At the risk of sounding like an "Onsagarist," I propose that entropy be used not as a measure

of the reversibility of a system, but as a measure of conversion of recoverable energy into nonrecoverable or dissipative energy. Furthermore, that the pragmatic approach to the utilization of entropy be not in the calculation of the conversion from stored energy to energy in motion, but rather in the determination of the time *rate* of dissipation of energy in the form of heat. This means that we are not restricted to Bates' PV versus TS diagrams, but can now consider interactions between forces and fluxes (in a general way, or if preferred, in the linear Onsagar Law way). Entropy considerations will tell us not only what the system will or will not do but will enable us to obtain a measure of the rate of energy dissipation.

To the student who has suffered through innumerable PV versus TS reversible-irreversible problems and lectures, *this* "moleculeless continuum mechanical thermodynamics" approach appears as an oasis in a desert of sand and bleached bones of archaic thermodynamicists.

Conclusion

If I seem unkind to present approaches to the teaching of thermodynamics, it is because my own experiences as a student are healing very slowly. Thermodynamics, or classical mechanical thermostatics, needs more than first aid. It is dying, and unless non-thermodynamicists recognize the malady as malignant consumption and act quickly, the do-gooders with their adhesive tape will shortly embalm the still-warm body.

I have tried to give an example of an entirely pragmatic approach to a very simple concept, entropy, and, more importantly, an illustration with regard to the direct engineering application of this concept to modern chemical engineering. This approach would almost certainly allow Gibbs to rest quietly — and I doubt that he *is* resting quietly now.

It is admitted that no mention has been made, either by Bates or me, of *chemical* thermostatics. For my part, I support the philosophies of Gibbs and Denbigh. Additional comments will be forthcoming.

REFERENCES

1. Balch, C., University of Toledo, personal communication, 1967.
2. Bates, H. T., *Chem. Eng. Ed.*, 1, 37-43, (1966).
3. Bird, R. B., Stewart, W. E., and Lightfoot, E. N., "Transport Phenomena," John Wiley, New York, 1960.
4. Coleman, B. D., and Noll, W., *Arch. Rational Mech. Anal.*, 4, 97-128, (1960).
5. Roller, D., *The Early Development of the Concepts of Temperature and Heat: "The Rise and Decline of the Caloric Theory,"* Harvard University Press, Cambridge, Mass., 1955.
6. Siedel, B., University of Delaware, personal communication, 1963.
7. Tribus, M., "Thermostatics and Thermodynamics," D. Van Nostrand, Princeton, N. J., 1961.

The Integrity of Chemical Engineering

J. M. Douglas

Associate Professor of
Chemical Engineering

S. A. Miller

Professor of
Chemical Engineering

University of Rochester, Rochester, N. Y.

Chemical engineering is a chemistry-and-physics based discipline. Chemical equilibria and kinetics share equal importance with physical equilibria and transport rates. The conservation statements about chemical systems are as significant as those about physical ones. Furthermore, the processing that accompanies chemical reactions in the manufacturing setting depends heavily on diffusive transport of molecular matter, an aspect of physical chemistry exploited predominantly by the chemical engineer. In this kind of physical operation there has developed peculiar identification with the chemical engineering discipline.

By combining chemical (stoichiometry, thermodynamics, kinetics), physico-chemical (diffusion, phase transformation), and physical (heat transfer, fluid mechanics, strength of solids) principles under the constraints of practical economics, chemical engineering has produced processes of great complexity, carried out in plants that are often enormous (ten million gallons of product per day) and costly (hundreds of millions of dollars). Chemical engineers are responsible for the entire plant and process—their conception, development, design, and economic operation — every component of which must operate properly with respect to all the others if success is to result. This is true systems engineering.

The history and present status of engineering and the engineering industries demonstrate that there is a distinct need and proper place for the peculiar educational experience that a chemical engineering curriculum affords, and for the product of that education. Chemical engineering problems are characterized, indeed, by a degree of complication greater than those usually identified with the other traditional engineering fields. The evolution of our discipline has brought with it methods of attacking such problems, and concepts of exceptional power and wide usefulness. A consequence is that chemical engineers, essential to the process industry, are in demand in a variety of other environments, industrial and extra-industrial. One of their great assets is their ability to work unusually effectively with representatives of other disciplines in the solution of problems of great scope and interdisciplinary character.

Notwithstanding the success of past advances, the techniques and insight provided by chemical

engineering are still evolving, and there is strong reason to believe that contributions arising out of them will be even greater in the future. Chemical engineering originated from the consolidation of the principles common to a number of previously isolated use-centers: the paper industry, petroleum refining technology, acid manufacture, et cetera. Its great strength derived from its capacity to unify and establish bonds between these otherwise diverse, discrete industries, and to provide education and training that make the chemical engineer effective in all of them. Today there seems to be some tendency again to fragment the field into use areas with new names but distinct identities: environmental engineering, food engineering, and the like. A competing tendency would generalize certain of the subdisciplines shared by several of the engineering fields into new disciplines: thermal engineering, materials science, and systems engineering are examples. In both cases, the identification of interest centers at which competences from a number of disciplines can converge for the attack of broad super-problems is useful and salutary. But to suggest that they should subordinate or supplant the established discipline of chemical engineering is to suggest the destruction of the burgeoning promise of tremendous future contributions originating in our field.

We submit that future society will benefit most from the maintenance and continued evolutionary development (at the most fundamental level consistent with the definition of the field) of an academic discipline erected on the subject matter at the core of chemical engineering today. Simultaneously, vigorous effort should be directed to those developments at or near the diffuse boundaries where other currently defined disciplines, basic and applied, and chemical engineering merge. We believe that such a frankly disciplinary approach optimizes the task of conserving and extending the treasure of knowledge, understanding, and skill for which chemical engineering has become a particular repository; of applying that treasure to new creative goals in the world of the process industry; and of sharing major interdisciplinary challenge with others in a significant effort which, in using without sacrificing its contributing collaborators, is enduringly synergistic.



INDEX FOR VOLUME 1 (1965-1966)

AUTHOR INDEX

Abraham, W. H.	30
Bates, H. T.	37
Berg, L.	12, 44
Burkhart, L. E.	1
Burnet, G.	(1) iv
Burr, A. A.	7
Chilton, T. H.	9
Christensen, J. J.	14
Douglas, J. M.	72
Genereaux, R. P.	27
Griffith, D. E.	1
Hamielec, A. E.	52
Hubbard, R. M.	10
Kenyon, R. L.	45
Kiser, K. M.	48
Levenspiel, O.	55
Madonna, L. A.	24
Miller, S. A.	72
Murphy, G.	3
Pfeffer, R.	13
Schmidt, A. X.	13
Snyder, J. R.	11
Thorpe, R. G.	63
Throne, J. L.	70
Wheelock, T. D.	5
Willis, M. T.	46
Wise, D. L.	24
Woods, D. R.	19, 52
Yerazunis, S.	7

SUBJECT INDEX

Bifurcation	1, 5, 3, 7
Career choice	12
Chemical Engineering Division	(1) iii, (1) iv
Cooperative programs	14
Core curricula	24
Curricula	1, 3, 5, 7, 14, 25
Design	(3) iii, 19, 52, 55
Engineering science	24
Entropy	70
Five-year programs	14
"Goals" Report	(2) iii
Industry, relations with	9, 27, 63
Integrity of Chemical Engineering	72
Interdisciplinary programs	1, 24
Job choice	12, 44
Laboratory demonstrations	10
Multifurcation	1, 3
Option, curricular	1, 3, 5, 24
Overhead projector	11
Process control (book review)	30
Professional challenge	45
Professional practice	9, 44
Reactor design	55
Reactor design (book review)	48
Rensselaer program	7
Science-oriented curricula	3, 7, 24
Teaching aids	10, 11
Teaching load	13
Thermodynamics	37, 70
Transport phenomena	46
Trouble-shooting	19
Unit operations	46
Visual aids	10



CHEMICAL ENGINEERING EDUCATION

201 Gavett Hall,
University of Rochester,
Rochester, N.Y. 14627.

November 17, 1967

Dear Subscriber:

No, there's nothing wrong with your mail service. It is your editors who are responsible for your receiving Volume 1, Number 4 of CHEMICAL ENGINEERING EDUCATION in November, 1967, instead of June, 1966. But although the masthead date shown on this issue is technically correct, you may be assured that the contents are contemporary. Copy for all of the material that it carries except the feature article was received within the last six months -- some of it, notably advertising copy, only a fortnight ago. And Professor Levenspiel's fine paper is certainly as readable today as it was in mid-66.

We are sorry for the delay. We hope that you find the issue rewarding in spite of having to wait for it so long.

The official publication of ASEE's Chemical Engineering Division will come to you in the future under new, extremely competent editorial leadership. I know that bright days lie ahead for all of us readers who are interested in chemical engineering education. Meanwhile John Bartlett, Al Cooper, and I are grateful for the privilege we've had to serve you and the Division during an interim period in the life of CHEMICAL ENGINEERING EDUCATION.

Sincerely yours,

S. A. Miller
Editor

SAM:sm

CHEMICAL ENGINEERING EDUCATION

201 Gavett Hall,
University of Rochester,
Rochester, N. Y. 14627.

Non-Profit Organization U. S. POSTAGE PAID ROCHESTER, NEW YORK Permit No. 780
