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chemical engineering education

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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

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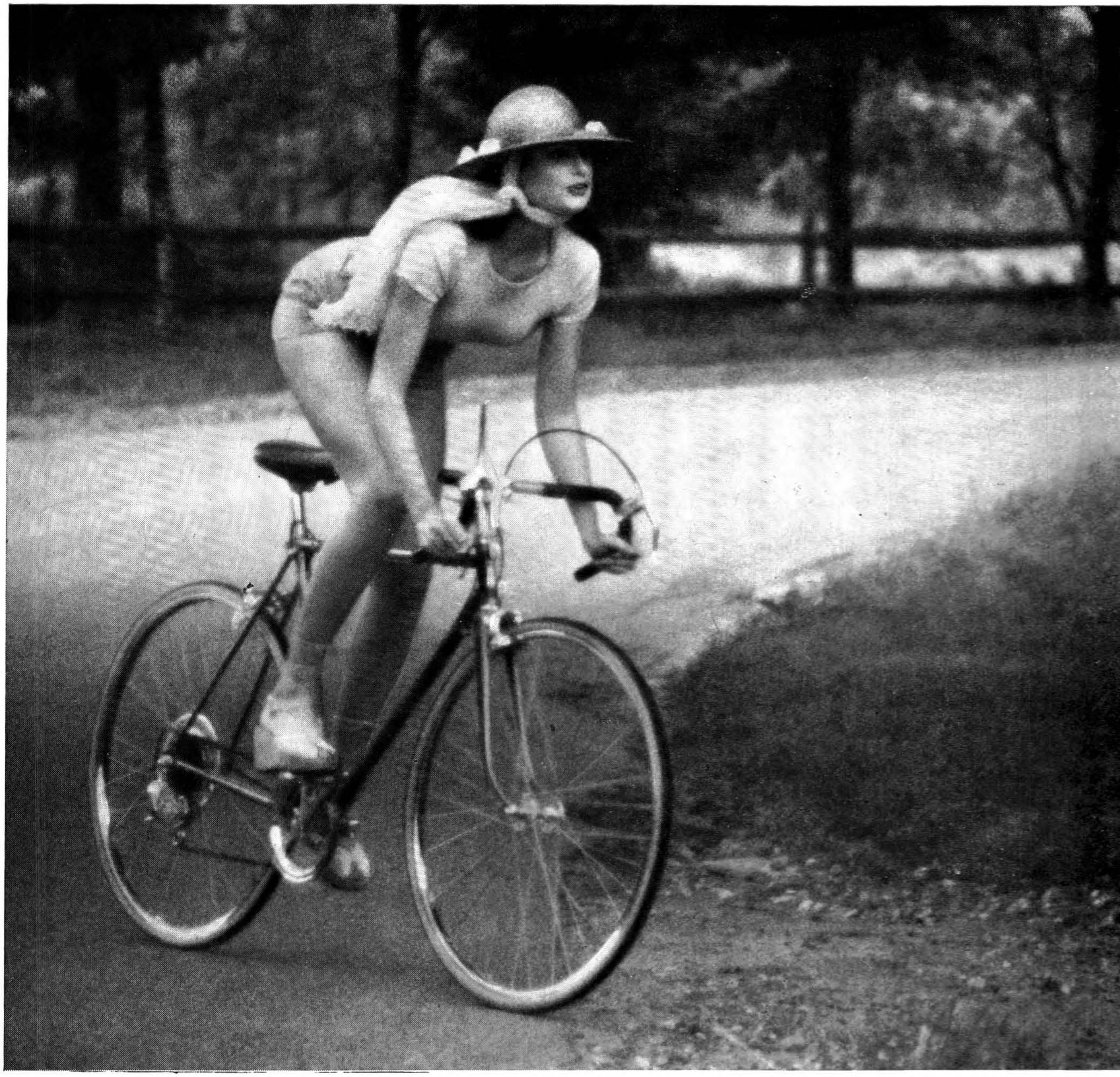

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Chemical Engineering Education

VOLUME XI NUMBER 4 FALL 1977

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Editorial

A LETTER TO CHEMICAL ENGINEERING SENIORS

This is the ninth Graduate Issue to be published by CEE and distributed to chemical engineering seniors interested in and qualified for graduate school. As in our previous issues we also include ads of departments on their graduate programs and some articles on graduate courses that are taught at various universities. However this year we are including a larger number of general papers on graduate education that we feel are of interest to both students and faculty and fewer courses. Therefore in order for you to obtain a broad idea of the nature of graduate course work, we encourage you to read not only the articles in this issue, but also those in previous issues. A list of these follows. If you would like a copy of a previous Fall issue, please write CEE.

Ray Fahien, Editor CEE
ChE, Dept., University of Florida
Gainesville, Florida 32611

In Memorium

Leon Lapidus

Professor Leon Lapidus, 52, chairman of the Department of Chemical Engineering at Princeton University, died suddenly in his office May 5, 1977.

He was the author of more than a hundred technical publications including four textbooks: *Digital Computation for Chemical Engineers, Optimal Control of Engineering Processes, Numerical Solution of Ordinary Differential Equations,* and *Mathematical Methods for Chemical Engineers.* Widely sought as a consultant, Lapidus was a member of the National Academy of Engineering, Sigma Xi, American Chemical Society, American Institute of Chemical Engineers, the Association of Computing Machinery, and president of the New Jersey Tennis Association.

The Princeton University Faculty adopted the following memorial resolution at its June 1977 meeting:

MEMORIAL RESOLUTION FOR PROFESSOR LEON LAPIDUS

Dr. Leon Lapidus first came to Princeton in 1951 as a Research Associate in Professor Richard H. Wilhelm's program in chemical sciences on what is now the Forrestal Campus. His previous training included two degrees from Syracuse University in the city of his birth, a doctorate from the University of Minnesota, where he was the first of a long line of outstanding scholars under the tutelage of Dr. Neal Amundson, and a post doctoral fellowship at the Massachusetts Institute of Technology.

In 1953 he became a member of the Chemical Engineering faculty as an Assistant Professor. He was promoted to Associate Professor in 1958 and to Professor in 1962. In 1970 he was appointed The Class of 1943 University Professor. From 1968 until his untimely death on May 5, 1977, he served as Chairman of the Department of Chemical Engineering. Throughout most of his tenure as Chairman he was the elected member from Division IV on the Faculty Advisory Committee on Appointments and Advancements, making his membership on that important committee one of the longest in the history of the university.

A teacher-scholar in the best Princeton tradition, Professor Lapidus was also a skilled administrator. Indeed, a colleague in another department recently observed that Leon was the ultimate exemplar of the ideal all-round faculty member because his research productivity increased as his administrative responsibilities grew.

With a rare gift of being able to communicate often abstruse and difficult material clearly and enthusiastically, Professor Lapidus gained a wide reputation as lecturer, and student ratings of his courses invariably placed them near the top of all courses in the University. His contributions to teaching were not limited to classroom instruction, however, inasmuch as he authored or co-authored four major textbooks, and in collaboration with his first mentor, Dr. Amundson, he edited the definitive work on chemical reactor theory, written as a memorial to the late Richard H. Wilhelm. In particular his books on digital computation and on optimal control theory have widespread use as teaching tools. The book on chemical reactor theory was published during the week of his death.

In 1955, just two years after joining the Princeton faculty, Professor Lapidus introduced a new course in numerical methods of computation. This course marked the beginning of his professional concentration on the application of numerical analysis and computer techniques to problems in chemical engineering. Over the years he extended the breadth and depth of this application with special attention to problems in the simulation, control and optimization of chemical process systems. More than fifty graduate students participated in this work, many of whom are now on major faculties throughout the world. The fruits of this work, comprising five books and some 135 articles in scientific journals, have had a major impact on the way engineers in general, and chemical engineers in particular, approach problems.

Many awards went to Professor Lapidus for his prodigious scholarship. He won the Professional Progress Award and the William H. Walker Award of the American Institute of Chemical Engineers. In 1976 he was electedto the National Academy of Engineering, the third member of the Princeton faculty so honored. He has been Chemical Engineering Lecturer for the American Society for Engineering Education. Reilly Lecturer for the University of Notre Dame, Lacey Lecturer for the California Institute of Technology, Mason Lecturer for Stanford University, DDistinguished Lecturer for the University of Michigan, and Organization of American States Lecturer at La Plata University in Argentina.

Widely sought as a consultant to industry, Professor Lapidus also served on the editorial advisory boards of the Journal of the American Institute of Chemical Engineers, the International Journal of Systems Science, The Chemical Engineering Journal, and he was Editor of Control Series, Blaisdell Publishing Company. He was also a member of the Visiting Committee to the Department of Chemical Engineering at the California Institute of Technology.

He was an active player and a promotor of tennis, especially among young people. At the time of his death he was president of the New Jersey Tennis Association. Furthermore, he transmitted his enthusiasm for the game to his children, Mary and Jay, both of whom he coached to tournament calibre. Jay, who will enter Princeton in the fall, is generally regarded as one of the most promising tennis players in the United States.

A devoted husband and father, Leon Lapidus most of all enjoyed those activities which included his close-knit, immediate family circle: his wife, the former Elizabeth Kalmes, whom he met and married in Minneapolis, Minnesota, and his children, Mary Kalmes and Jon Jay.
In addition to his immediate family he leaves a sister, Mrs. Florence L. Goldman. He leaves, too, a large number of friends and colleagues, who will deeply miss those personal and professional qualities that made so lasting an impact on his profession, on Princeton University and on the Department.

Ernest F. Johnson
William R. Showalter
Richard K. Toner

ChE letters

FACULTY WORKLOAD CORRECTION

Sir:

In the interest of accuracy, I would like to state that my paper in *Chemical Engineering Education*, Vol. II, No. 3, p. 134, 1977 should be entitled, "Faculty Workload Measurement," and not "Faculty Workload Measurement at NJIT."

I would appreciate having this fact brought to the attention of your readers since the article is not how loads are measured at NJIT. Thanks.

Deran Hanesian
New Jersey of Technology

EDITOR'S NOTE: CEE deeply regrets the error.

ChE book reviews

FINANCIAL DECISION MAKING IN THE PROCESS INDUSTRY

by Donald R. Woods, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1975. 324 pp., $16.95.

Reviewed by Vincent W. Uhl, University of Virginia, Charlottesville, VA.

The treatment seems to go beyond the title; in introductory chapters the books surveys two important areas related to financial decision making. One is that of the professional making judgements which affects society and the world we live in. The other area is the overall business environment. By this approach Woods manages to scan the full sweep, the spectrum from the individual to society. Then he concentrates on "process economics" in this setting.

Process economics constitutes the core of the work. Basically the methodology delineated is

Continued on page 188.

ChE views and opinions

THE INTERFACE BETWEEN INDUSTRY AND THE ACADEMIC WORLD*

EDITOR'S NOTE: Prof. Shinnar's paper was presented at an Engineering Foundation Conference on Chemical Process Control at Asilomar, Pacific Grove, CA, Jan. 18-23, 1976. We thought it worthwhile reading for students and faculty alike.

REUEL SHINNAR
The City University of New York
New York, New York 10031

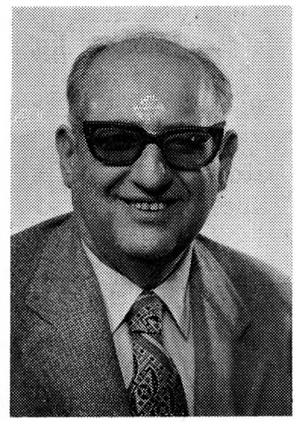
I CAME TO THE academic profession quite late, after many years in industry, and my values and outlook were formed during my industrial career. Having worked in many fields and having had a varied career gives one the advantage of an overlook, and one often sees things that an insider cannot see. This paper is about some of these impressions on the present status of control.

Let me start with three episodes that happened to me recently and induced me to choose this topic for presentation. The first was a question asked of me by the chairman of one of the top chemical engineering departments in the United States. He asked me if process control today is still an active field of research in ChE and if it makes sense to have somebody in this field. It was an honest question, which is also asked by quite a few others, even those who have been active in control in recent years and are now leaving it. I'll try to answer it later.

The second occurrence was a letter I received from a former student of mine who obtained his Ph.D. in the U.S. in the area of control. I sent him a recent paper *(1)*, and in commenting on it he complained that our engineering profession is so far backward in the application of novel ideas in control that he has decided to go where the action is and become an applied mathematician.

The third happening was a comment by a reviewer that Vern Weekman received on a paper of his. The reviewer complained that the authors were unfairly criticizing the academic world, since he questioned how an academic could know what is and what is not implementable in industry. I don't know who here was hard on whom. I can hardly imagine a more severe condemnation of our academic engineering profession than this statement. If engineering professors have ceased to know what can and cannot be implemented, what are we teaching?

In these three episodes there is a reflection of the whole sad state of research in process control as well as an indication as to what needs to be done.



Reuel Shinnar is Professor of Chemical Engineering at City College, N.Y. He is known from his publications in reactor design, process dynamics and control, crystallisation, fluid dynamics, and combustion. A special interest of his is the application of probability and stochastic processes in engineering. Professor Shinnar received his B.S. from the Technion in Haifa, and his Ph.D. from Columbia University. Before taking up an academic career he worked for ten years in industry and still consults to the chemical and petroleum industry.

THE STATE OF PROCESS CONTROL

LET US NOT avoid the issue; the state of process control is rather sad. True, we have had

*Reprinted by permission from AIChE Symposium Series. Vol. 72, No. 159, p. 166.

many important theoretical and mathematical advances in recent years, and, as Professor Athans' paper [8] pointed out, quite a number of them could be very significant, and I definitely agree with him. But on the other hand, the application of these advances in industrial practice has been rather meager, and even those that are active in designing controls for completely automated complex plants complain that the publication of the academic community seem to be irrelevant to any conceivable needs. Furthermore, some of our best people are leaving the field disenchanted, and it is not attracting top students as often as previously. This is happening just as exciting applications are starting finally to appear, and, there are definite trends in industry that will require a better understanding of modern control.

But even in industry the love affair with process simulation and control is cooling. The heat is on almost all the research groups in the industry. Maybe we started too early and promised more than we could fulfill. But we could reasonably expect more understanding from industry. Let me remind you that the total expense of any major oil company on research in process control in any given year is less than for one major television commercial, and there is less evidence that commercials sell gasoline.

Somehow I feel that some of the recent adadvances in control theory offer exciting possibilities for better design, but there is very little knowledge as to what these values really are, where they can be successfully applied, and what the pitfalls are, and there is no question a lot of it is irrelevant.

Just look at the tremendous literature on Kalman filters. We listened to some top practitioners and heard that only one had ever really used one successfully. Listening to him, I realized that he used it in a different way than it is presented in the control literature, as a tool in interactive computer-aided design in which the coefficients are guessed and continuously adjusted by the results of the simulation. Now I would like you to relook at the literature on Kalman filters. How much of it really deals with the basic problem, which is to decide how to guess the structure of the covariance and, furthermore, to decide in what cases it is going to be useful.

Listening to the two sides of the arguments on the usefulness of modern control reminded me of two other episodes that happened to me. You have to excuse my habit of telling stories. In my culture it is a basic belief that a short story or joke often replaces a thousand words.

During the Israel Independence War in 1948 I was engaged in the manufacture of explosives and ammunition. Once I faced the problem of designing a simple small siren intended to be put on small bombs, to increase their psychological effect. I had no idea how one designs a siren and was looking for some sketch to copy. To save time I went to a professor I knew, and I still remember him going to his shelf and giving me two volumes of "Das Handbuch der Theoretischen Physik." I was reminded of this story by the claim that modern control theory is there—just go and use it.

The second episode symbolizes for me the stand of some of our industrial assessment members. In the early 1950's a group of young engineers were sitting in a house in Haifa and reminiscing about the war. One fellow recounted his experiences in the British Corps of Engineers. The British Army instructions at that time required that prefabricated pre-stressed concrete slabs should be reinforced in all four corners. Now, every compentent engineer knows that we only need two reinforcements, in the two corners on the lower side. One guest was an old Englishman who had stayed in Israel, and he commented that we were all a little young and inexperienced and did not fully appreciate the wisdom of the British Army. The manual is intended for use by the average sergeant in the British Army, who as likely as not is a Sikh with a minimum understanding of English.

There are probably many really valuable results hidden in the literature of modern control that merit being brought to a form useful for the control engineer. But we need to extract them, test them, and bring them to a form where they are useful tools in real empirical design.

He might be the only one in the company who can read that manual. You have to imagine him standing there with his curved knife in his mouth studying the manual, and, when he takes out the knife and starts to yell, you hope he'll know where to put the slab. If you presume that he'll know which side is up, you have lost in advance.

The Ziegler-Nichols tuning method of PI controllers almost fulfills the same requirement. But modern process control is never going to have a reinforcement in each corner. This is not its objective. It will need highly educated engineers to use it for special applications where it is justified. But it is also useless to tell industry, "There are two thousand mathematical lemmas, and why don't you use them?" As almost all assessment reports agree, modern control theory is not in a state where it is easily used.

ACADEMIC-INDUSTRIAL INTERFACE

THE PROBLEM IS really at the interface. The information flow from academics to industry and back is jammed, and the question is what we can do about it.

It would be very valuable if the process industries would publish more about their successes and failures. Some of the secrecy surrounding control is really bordering on the ridiculous. But it is rather hard to hope that they'll really do it in a useful way. The aerospace industry has much less of a problem, since much of the work is government financed and therefore published, and it also employs a much larger number of theoretically educated engineers.

If we want to improve that interface, it is the engineering societies and, above all, the engineering faculties who can and should do this job.

I don't worry about algorithms or computers eliminating the engineer. Complex design algorithms need a much higher degree of intellectual input than present methods and increase the need for highly trained personnel.

As a profession, engineering is not a science but rather the knowledge of bringing scientific development into useful practice, very often making empirical advances before the scientist understands them. Even design, which is much more formalized, is only partly based on scientific calculations and relies heavily on intuition and experience. Part of it can be computerized and formalized, but in the end judgment will play a large role in the synthesis.

Now design or process development is not easy to teach and much harder to do research on. To promote good research we have more and more gone over to focus our research on hard science, picking up areas left by the physicists and chemists, and slowly we have become a professional taught by non-practitioners. Maybe we are the only profession to do so. Can you imagine a medical school where all professors are physiologists and nobody is a clinician? Now medical research is much less clean and less scientific than physiology, but the latter would have no application without the first.

I see nothing wrong in having a large part of our research devoted to clearly definable scientific problems, both theoretical and experimental, but somehow we have to make an attempt to bring engineering back to our research. Nowhere is this more felt than in theoretical engineering and especially in control.

PROCESS CONTROL DESIGN

THERE ARE SEVERAL needs in engineering design that good theoretical research can fulfill.

- **The first is a need for straightforward algorithms, as, for example, the measurement of kinetic parameters in complex systems.**
- **The second is a need to better understand design decisions. Theoretical work can contribute to that by solving clearly defined cases, illuminating to the engineer what the potential problems could be. A good example of this is the theoretical work in reactor design, an area in which I also contributed. Now, in very few industrial cases would one expect an engineer to solve the type of complex models that have been solved or discussed in the literature. Hopefully, my own students do not interpret their work this way. However, from such theoretical modeling and related work we delivered rather well-working principles for reactor design: how to identify kinetic parameters in a simple way, how to structure the experiments needed for scale-up, how to identify reactors, and, most importantly, how to distinguish between simple problems and those which require more advanced methods. This is the most fruitful area for theoretical engineering research. But in order for it to be really useful the results have to be explained to the practicing engineer in a form he can understand.**

There are other types of theoretical research that I took part in. Some of the most difficult problems solved often only confirm that methods used by the engineer have a sound basis, but they do not lead to new insights.

Years ago when I worked in rheology, everybody was busy for years trying to understand the complex work of Coleman and Noll on constitutive equations. I don't want to belittle the eloquence and relevance of that work to continuum mechanics as a theoretical science. But the insight that we got from that to real rheology, and especially

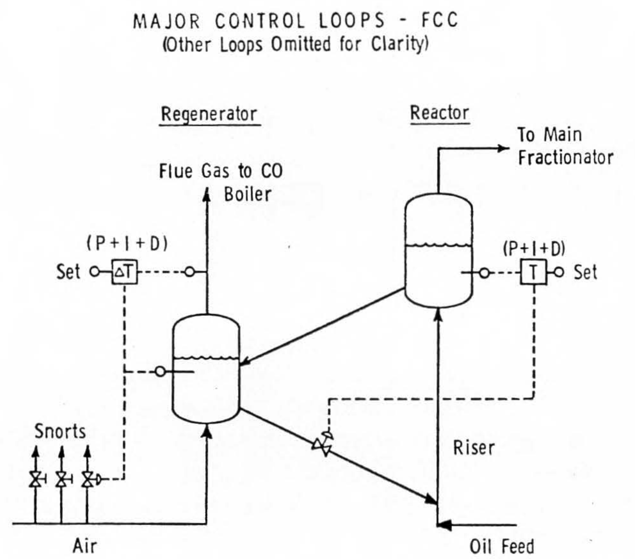


FIGURE 1. Schematic of conventional control scheme.

to problems of interest to the engineer, was rather small. We learned that a capillary rheometer measures the same parameters as a cone and plate viscosimeter and that it is impossible from such measurements to predict the behavior of the liquid in accelerating flows. We knew that long before. But we learned little about how to treat those more interesting cases and had to go back to simpler and more *ad hoc* theories. I admit of having done similar things myself. It did not start out that way.

The best way of describing such work from an engineering point of view is maybe the expression of Moliere's hero in the *Bourgeois Gentilhomme,* "I never knew I speak prose." There is some importance in knowing that one speaks prose, and from a purely scientific point of view this is often very interesting. But the importance that we give to such mathematical rigor in our engineering profession has little relation to its real value to the profession.

The fourth type of theory is the one that leads nowhere. I remember a good example from the time I was a graduate student. At that time a fashionable pastime was to write down equations of mass transfer in multicomponent systems. Some of these equations were tensors of the sixth or eighth order. There was no way that anybody could ever measure that many coefficients or even design a hypothetical experiment to measure them. The only thing we learned is that too much rigor will lead to unsolvable problems.

Now in engineering we start to give the highest ranking to the "I know prose" research and much less to that which leads to real insights in design. Nor do we insist that our results be presented in such a way that such insights to dirty problems are made clear. We have to learn to appreciate both types of research.

Consider for example the study of FCC control by Kurihara [2]. It is a very useful piece of work, and let me therefore discuss it in more detail.

Kurihara took a fluidized bed cracker and developed a simple lumped parameter model for it. He then took the standard industrial control scheme which is given in Figure 1, taken from Lee and Weekman [3], and looked at the connections between measured and manipulated variables. He then formulated an optimization problem in the following way. The system is assumed to be at a state X, different from the desired steady state, and has to be brought back to the desired steady state. At this desired steady state, all manipulated inputs have a known value. The feedback law is then written to minimize a performance index using some values for costs of control action and for profits based on reducing the deviation from the desired steady state. It is shown that a linearized analysis gives a very similar solution to the full non-linear optimization and furthermore, the control scheme given in Figure 2 gives almost the same result.

Now, there is much more in the thesis than I

Continued on page 191.

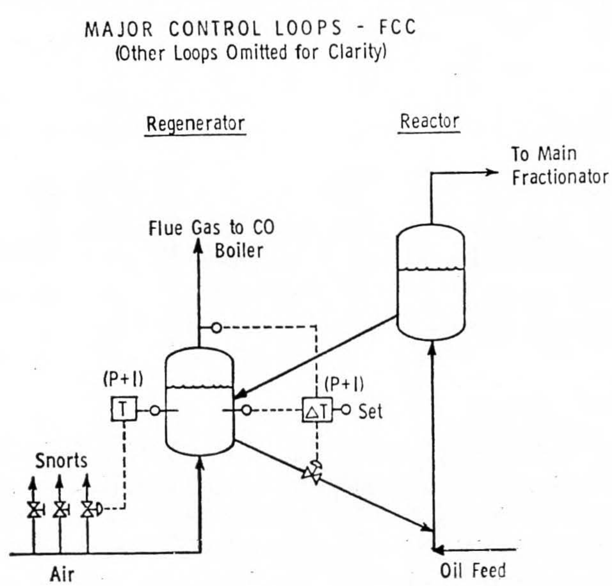


FIGURE 2. Schematic of Kurihara scheme.

TECHNICAL PROSE: ENGLISH OR TECHLISH?

H. C. VAN NESS and M. M. ABBOTT
Rensselaer Polytechnic Institute
Troy, New York 12181

IF THE SENIOR CHEMICAL engineering student feels burdened by report writing, he can take no comfort from what lies ahead, for writing will likely occupy an even greater proportion of his time as a practicing engineer. Moreover, success will depend as much on development of communication skills as on technical ability.

One learns to write just as one learns to ride a bicycle, to play a musical instrument, or to make love. Bad performances are not only common, but easily recognized. Remedial instruction is by criticism and example. Unfortunately, professors are seldom accomplished writers, and provide far more bad examples than good. Thus by the time a student is required to write a technical report he slips naturally into a special written language, which we call Techlish. Fortunately, it bears some relation to English and a literate engineer can often understand its general drift, if not its precise meaning.

Take a straight-forward English sentence: *He followed her in hot pursuit.* Not one engineering student in a hundred would put to paper any thought so directly and so evocative of an image of what is afoot. Translated into Techlish, it becomes, *It was she who was followed by him in hot pursuance,* or perhaps, *It seemed necessary that he should heatedly follow her in a pursuit-type mode.*

THE STUDENT REPORT

EXAMPLES OF FULL-BLOWN Techlish abound in almost any student report, and we quote verbatim in what follows from several that were submitted in a process-design course. Consider the punch line, the final sentence, of one report: *The finalized design appears promising and the results of this study urges further pursuance.* One notes the ungrammatical combination, "the results . . . urges", wherein the subject and verb do not agree in number. Although such errors are common in student reports, they are not essential to Techlish. The grammatically correct expression, "the results . . . urge," illustrates a basic characteristic of Techlish, namely, the combination of words which in common use do not belong together. Results do not urge; people urge: *She urged him on in hot pursuit.* Other unhappy word choices are "finalized" for "final" and "pursuance" for "pursuit". Another characteristic of Techlish is the total lack of assignment. To whom does the design "appear promising"; who is to pursue the matter further? But the crucial problem is that we are not sure what the author means. The distinctive quality of Techlish is that it always confronts the reader with this problem. Translated directly into English, the sentence reads, "The final design may not be final." However, as a sentence from a student's report its true message is probably: "I hope the design is reasonable; if not, further work should make it so". The student is really suggesting to the teacher that he deserves a good grade in either event.

Not only does habitual use of the passive voice make for dull writing; it forces a convoluted style almost impossible for an engineer to make concise, precise and grammatical.

We start with this last sentence of a report because it points to a basic problem for the student. He is asked in a design course to assume the role of a practicing engineer writing a report for his supervisor. In this role, his objective is to provide information that will allow his supervisor to make some sort of recommendation to higher management. Large sums of money may be involved; employee safety and public health may be considerations. Such matters are not trivial, and the author of the report is assumed expert with respect to his subject. For a student to play this role successfully, he must suppress his natural propensity to behave as a student whose sole objective is to impress his teacher and to earn a good grade. The transition from pupil to expert is abrupt, and few students can believe it is expected, let alone respond properly. Thus student reports are laced with all sorts of irrelevant material that no supervisor would care to read, but which is thought to impress a teacher. There are, for example, long discussions of what was *not* done, comments on the great difficulty or extent of the calculations, narrative expositions of step-by-step calculations, derivations of standard equations copied from readily available sources, and convoluted excuses proffered in compensation for an inadequate effort. One finds such gems as,

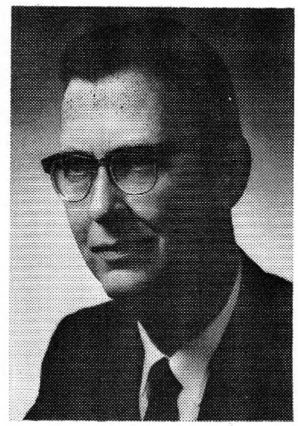
> *This is a close approximation, since the whole process was designed by a series of approximations.*

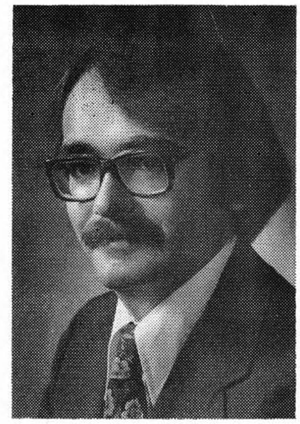
The logic is of course absurd, but the student feels he should suggest some reason for the teacher to accept his result.

A report must be written with the intended reader in mind. This is the cardinal rule of report writing. A process-design report goes to the boss. In a design course the student has no real boss, but must imagine one. Although the teacher grades the report, he is not the boss; he merely judges the report with respect to its acceptability to an imagined boss. When writing for the boss, either real or imagined, one may safely assume that:

1. He is busy, or at least believes he is, and
2. He has a general technical knowledge at least equal to one's own.

The report is written to help the boss; it must not waste his time. He is interested in the results and their justification, and these must be the focus of the report. They must occupy a prominent position in a separate section or sections. They do not belong in the abstract, the introduction, or the conclusions. They must be stated concisely, with authority, and without ambiguity. Figures and tables are appropriately used to aid clarity and to summarize and order results succinctly; each must be numbered and referred to in the text. A process description is always written with reference to a carefully labelled diagram.





H. C. Van Ness is Distinguished Research Professor of Chemical Engineering at Rensselaer Polytechnic Institute, where he has been a faculty member since 1956. He is coauthor with J. M. Smith of "Introduction to Chemical Engineering Thermodynamics", 3rd. ed., McGraw-Hill, 1975. (Left)

M. M. Abbott is Associate Professor of Chemical Engineering at Rensselaer Polytechnic Institute, with which he has been affiliated since 1969. Prior to that, he spent four years with Exxon Research and Engineering Company in Florham Park, New Jersey. (Right)

Professors Abbott and Van Ness are coauthors of a number of research papers on thermodynamics and of two books: "Schaum's Outline of Theory and Problems of Thermodynamics", McGraw-Hill, 1972, and (with M. W. Zemansky) "Basic Engineering Thermodynamics", 2nd. ed., McGraw-Hill, 1975. They do not guarantee these works to be free of Techlish, but have made a conscious effort to follow their own rules.

Although the results of a report are presumed the work of an expert, the boss will likely check them at least in part. He must find this an easy task through reference to an appendix, where all calculations are carefully laid out and thoroughly annotated.

No universal agreement exists as to the proper format of a report, and we can suggest none. The reasons are, first, that the nature of the report should influence the format, and second, that the style of a report and hence its format should reflect the individuality of the writer. However, an abstract is essential, as it tells a prospective reader what is in the report. An example of a suitable abstract of a process-design report is:

> *A preliminary design of the heat-recovery unit for a plant to produce shale oil is described. Circulating gas picks up heat from a moving packed bed of spent shale and transfers it to raw shale in a similar bed. Technical feasibility of the process is demonstrated.*

One needs no more than this to know what the report is about. It is brief, to the point, and it stands by itself.

Unless it is very short, the body of a report is divided into sections. Students are often given a list of "standard" section headings, such as,

Introduction
Procedure
Results
Discussion
Conclusions and Recommendations

These may or may not be appropriate for a particular report prepared by a particular individual. The report abstracted above might well be divided according to the headings:

Process Description
Heat Recovery from Spent Shale
Preheating the Raw Shale
Auxiliary Equipment
Recommendations

Appropriate headings are also used with appended material, such as notation, literature citations, and calculations. In our view the introduction, which simply sets the stage, needs no heading. What else could the first several paragraphs of a report be?

PRINCIPLES OF WRITING

WE RETURN NOW to our main theme, the language of a report, the writing of technical prose. Engineering students often are convinced of several misconceptions about writing:

1. **Engineers are naturally poor writers.**
2. **Writing is not important for engineers.**
3. **The rules for writing technical prose are different from those for non-technical prose.**

The first two misconceptions tend to go together with some sort of reciprocal justification, and we simply contradict them. The third is a mistaken impression gained from wide exposure to Techlish. Here we can by example show the difference between Techlish and English. But first we offer a few general principles designed to guide one away from the most objectionable excesses of Techlish.

I. Be concise; be brief; eliminate "bull." Provided you recognize it when you see it, "bull" is effectively pruned as follows: Write a first draft, put it out of sight and mind for a day or two, then rewrite it, cutting the length by 25% or more. This process can usually be repeated.

II. Be precise; be specific; say what you mean; avoid ambiguities. Your work is too important to be misunderstood. Your sentences must make literal sense. Read them aloud; change any that sound ridiculous. You can gain experience with whatever you read; an example is the following sentence from an official university bulletin: *Faculty, staff, and students are asked to cut back on energy waste by the President.*

III. Prefer the active voice. The active voice results when the subject of the sentence *carries out* the action implied by the verb:

We calculate density by the ideal-gas equation.

In contrast, the passive voice results when the subject of the sentence receives the action implied by the verb:

Density is calculated by the ideal-gas equation.

One learns to write just as one learns to ride a bicycle, to play a musical instrument, or to make love. Bad performances are not only common, but easily recognized. Remedial instruction is by criticism and example. Unfortunately, professors are seldom accomplished writers, and provide far more bad examples that good.

This sentence does not say who does the calculation; it is impersonal. Herein lies the origin of Techlish. For many years the dominant attitude with respect to scientific and technical writing was that it should be impersonal, because science and technology were said to be impersonal. This forced adoption of the passive voice, and promoted the lifeless syntax, the witless style, to say nothing of the grammatical mistakes of technical prose. We repudiate the whole of it. Not only does habitual use of the passive voice make for dull writing; it forces a convoluted style almost impossible for an engineer to make concise, precise, and grammatical. *I* and *we* are not four-letter words; they are entirely acceptable in technical reports and publications. We do not suggest that every sentence start with *I* or *we;* one seeks variety. If you are too humble or shy to bring yoursel to write *I,* use *we,* in the sense of you, the reader, and I, the writer. *One* also has its place. Do not think you can avoid responsibility for what you write by adopting an impersonal style. No way; your name is on the title page. Take some pride in it; you are the expert.

IV. Write in the present tense, unless it is clearly inappropriate. In some technical writing, changes of tense are nearly as numerous as sentences. In student reports one often finds past, present, and future tenses all in the same paragraph, even in the same sentence. This confuses the reader, and is usually senseless. The results given in a design report are of course determined in the past, but they still exist, and should be presented and discussed in the present tense.

V. Avoid Techlishese. This heading covers a variety of literary vices:

(a) Jargon, elongated or fancy words. For example:

> **"Finalized" for 'final"**
> **"Pursuance" for "pursuit"**
> **"Utilize" or "utilization" or "usage" for "use"**
> **"Systematize" for "order"**
> **"Synthesize" for "make"**
> **"Hypothesize" for "assume"**

(b) "Using" (and its variants) as a preposition. Examples:

Density is calculated using the ideal-gas equation.

> **. . . by using . . .**
> **. . . by use of . . .**
> **. . . by utilizing . . .**
> **. . . by utilization of . . .**
> **. . . by making use of . . .**

In each case the simple preposition *by* adequately replaces the verbal expression.

(c) Possessives. Possession is usually associated with living things: "the consultant's fee," "the horse's mouth." An expression such as "the heat exchanger's tubes" is at best graceless. To speak of "Martha's tubes" might also be graceless, but is syntactically proper.

Note also that "it's" is not a possessive, but a contraction of "it is."

(d) "Due to" is not a synonym for "because of." It means "caused by":

The fire was due to a weld rupture.

Compare the following sentences.

Techlish: *Due to the fact that the pressure was low, the ideal-gas equation is used to calculate density.*

English: *Because the pressure is low, we calculate density by the ideal-gas equation.*

(e) "So" is not a co-ordinating conjunction, and does not mean "therefore" in formal prose.

Techlish: *The pressure is low, so we calculate density . . .*

English: *The pressure is low; therefore we calculate density . . .*

Note the semicolon which separates the two independent clauses of the second sentence; use of a comma here is wrong.

VI. Shun the dangling modifier. A verbal phrase at the beginning of a sentence must refer to the subject of the sentence:

Being hotly pursued, she saw the garden ahead.

"She" is the subject of the sentence, and "she" is being pursued. The logical relationship is more evident if we transpose the verbal phrase:

She, being hotly pursued, saw the garden ahead.

Note that we cannot put this verbal phrase at the end of the sentence without producing an absurdity:

She saw the garden ahead being hotly pursued.

Forced to write in the passive voice of Techlish, the engineer likely recasts this sentence into something like:

Being hotly pursued, the garden came into view.

Presumably the garden is not being pursued, but we cannot tell that from the sentence. "Garden" is the subject of the sentence, and the verbal phrase, regardless of its location, refers to the garden:

The garden, being hotly pursued, came into view.

The garden came into view being hotly pursued.

Do we find this sort of nonense in technical writing? In fact, we do, frequently. Consider:

To calculate the gas density, ideality is assumed.

The subject of the sentence is "ideality"; the verbal phrase "to calculate" must refer to it. Does "ideality" do the calculation? Try it the other way:

Ideality is assumed to calculate the gas density.

Even if we understand the sentence, it does not reveal who does the calculation or who does the assuming. The verbal phrase is said to dangle. In contrast, we have the unambiguous statement in the active voice:

To calculate the gas density, we assume ideality.

There are other possibilities:

Techlish: *Assuming ideality, the gas density is calculated.*

English: *Assuming ideality, we calculate the gas density.*

Entirely proper sentences can also be constructed with the verbal phrase as the subject of the sentence:

Assuming ideality allows calculation of the gas density.

Calculating the gas density is simplified by the assumption of ideality.

The richness of English derives from the many possible arrangements of words by which a message may be expressed; however, we can suggest nothing more direct or clearer than:

We calculate density by the ideal-gas equation.

We have stated an absolute rule respecting verbal phrases at the beginning of a sentence, because that is the usual location of the most insidious dangling modifier. However, verbal phrases can dangle in other locations, and clarity, if not grammar, requires that they be revised out of technical prose. The test of whether a phrase dangles is simple enough: If it is obvious from the sentence who or what is doing what the verb implies, the phrase does not dangle.

VII. Heed rules of particular importance to technical writers.

(a) Units. Most numbers are associated with units, and these must be clearly expressed. For this purpose pick conventions and stick to them. Many possibilities exist; for example:

4(atm)	or 4 atm.	or 4 atm
12(cm)	or 12 cm.	or 12 cm
$17(\mathrm{cm})^3$	or 17 cu.cm.	or 17 cu cm
30(ft)/(s)	or 30 ft./s.	or 30 ft/s
$24(\mathrm{J})/(\mathrm{s})(\mathrm{cm})^2$	or 24 J./s.-cm.^{2}	or 24 J/s-sq cm

(b) Symbols and numerals. Do not begin sentences with them. The simplest reason is that one runs into conflict with the capitalization rule for the first letter of a sentence. How does one write an upper-case 2?

Two liters of water are added.

Not

2 liters of water are added.

Is the symbol q capitalized at the head of a sentence?

The symbol q represents heat.

Not

q (or Q?) is the symbol for heat.

(c) Hyphens. Technical language abounds with groups of words that serve as a single adjective; hyphenation is required when such adjectives modify a noun:

ideal-gas equation
constant-presssure heat capacity
standard-state fugacity
2-inch pipe
heat-exchange fluid
220-volt circuit
4-foot-long duct

The hyphens connect all words which alone do not modify the final noun. Thus in ideal-gas equation, we are writing about neither an "ideal equation" nor a "gas equation"; in constant -pressure-heat capacity, "constant" modifies "pressure" and the compound adjective "constant-pressure" modifies "capacity", which is also modified by "heat". The reason for this rule is that without it one cannot make the necessary distinctions between, for example:

one armed bandit	**and**	**one-armed bandit**
a high school girl	**and**	**a high-school girl**
3 foot-long tubes	**and**	**3-foot-long tubes**

(d) Bibliography. Reference is frequently made in technical writing to outside sources of information. The use of footnotes is not generally satisfactory, and references are usually collected in a separate section at the end. A consistent format for all references is essential in this section; pick one, and stick to it. The current trend is to include the title of the reference. For example:

1. **Seeder, A. B., and V. D. Chitnis, "Laser Technology in Ancient Greece," J. Early Physics, 6, 4298 (1977).**

In the text, reference is usually made to this entry by a number in parentheses:

Seeder and Chitnis (1) report that . . .

Note that "in Perry" is not a proper reference to the Chemical Engineers' Handbook, no matter how widely known it may be. This volume is listed in the Bibliography as:

2. **Perry, R. H., and C. H. Chilton, editors.** Chemical Engineers' Handbook, **5th ed., McGraw-Hill Book Company, New York, 1973.**

EXAMPLES OF STUDENT PROSE

CONSIDER NOW SOME typical examples of student prose. Occasionally one finds a short, plain sentence:

The number of tubes was economically determined.

Unfortunately, brevity and simplicity are outweighed by faults. The passive voice and past tense don't help, but the real problem is that the sentence does not say what is meant and misses the opportunity to convey important information.

The design of a heat exchanger obviously requires determination (economically or otherwise) of the number of tubes; it is this number that is important. The sentence should be replaced by:

The most economical number of tubes is 145.

This is a positive, definite statement devoid of "bull".

Another short, plain sentence:

Make-up gas was calculated from energy considerations.

This one is plain nonsense. Gas (make-up or any other kind) cannot be calculated; calculation gives an amount or a rate. "Energy considerations" is too indefinite. What kind of considerations? Again, the sentence should be replaced by a positive, specific statement, such as,

An energy balance yields the make-up-gas flow rate.

One can understand the following sentence, but it is pure Techlish:

Using the McCabe-Thiele method, 34 equilibrium stages were necessary.

Thus, by the time a student is required to write a technical report he slips naturally into a special written language which we call Techlish.

Who is "using the McCabe-Thiele method?" Certainly not the "34 equilibrium stages" as is implied by the sentence structure. The 34 stages were necessary. Is this true now? The sentence is easily translated into English.

The number of equilibrium stages, calculated by the McCabe-Thiele method, is 34.

or

The McCabe-Thiele procedure yields 34 equilibrium stages.

"Using" (and its variants) is the most overworked word of Techlish; revision of a sentence to exclude it almost always results in improvement. This is true also of such common Techlish expressions as "it was necessary" and "in order to":

Techlish: *In order to maintain isothermal conditions it is necessary to cool the reactor.*

English: *The isothermal reactor requires cooling.*

Techlish: *In order to calculate the tower required, it was necessary to have vapor-liquid equilibrium data. This data was found by use of vapor pressures and assuming ideal solutions and ideal gas (Raoult's Law).*

English: *Raoult's law provides the vapor-liquid equilibrium data required for calculation of the number of trays in the tower.*

The last example of Techlish is so bad as to make a complete list of faults impractical. We note the following:

- **Passive voice.**
- **Past tense.**
- **"to calculate" refers to "it," and is a dangling verbal phrase.**
- **Evidently a tower is calculated. Absurd.**
- **Techlish: "In order to," "it was necessary," "by use of".**
- **"This data was . . ." "Data" is the plural of datum, and requires plural modifiers and a plural verb: "These data were . . .", or "these data are . . ."**
- **Non-parallel construction in the second sentence: "by use of . . . and assuming"**
- **An explanation of Raoult's law. Why insult the boss's intelligence?**

The following is an example of an inappropriate narrative style:

In this design of this heat transfer system we assume the moving bed to be a packed bed throughout the duration of this operation. To assure we have a packed bed system we had to find the superficial fluidization velocity. Our fluidization velocity was equal to 1905 ft/hr. When finding the dimensions of the preheater and post-cooler we need superficial velocities which were at most 75% of the fluidization velocity.

The translation into English:

Gas velocities through the moving packed beds of the preheater and post-cooler are no greater than 1430 ft/hr, about 75% of the fluidization velocity.

The story-telling version is of course replete with "bull", which when squeezed out reduces the length by two-thirds. Other problems with the Techlish text:

- **"this design," "this heat transfer system," "this operation." Is it clear what each "this" refers to?**
- **Multiple changes in tense.**
- **Lack of hyphens in "heat-transfer system" and "packed-bed system."**

Continued on page 173.

A Course in

FUNDAMENTAL CONCEPTS IN SURFACE INTERACTIONS

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AN IMPORTANT PART of chemical reaction engineering is the "design" of heterogeneous catalysts; and, in general, this design process rests both on (1) experience (e.g. correlations of catalytic activity and selectivity with the catalyst's solid state and surface properties) and (2) a fundamental understanding of the interaction of surfaces with adsorbed species. While the former aspect of catalyst design is already well established in ChE graduate training, the concepts contained in the latter are not usually encountered in ChE graduate curricula. Instead, the student must combine several courses—for example, in quantum chemistry, statistical mechanics and solid state physics—in order to cover the essential features of surface interactions. Yet, this approach does not provide the continuity that is necessary for effective application of these concepts to catalytic phenomena.

One possible solution to this problem is to develop a one-semester introductory course to the fundamentals of surface interactions and their applications to adsorption and catalysis; by stressing the physical, chemical and catalytic breadth that is necessary for the understanding of surface phenomena, the course can be given to first-year graduate students without prerequisites. Subsequent to this course, a student with special interest in surface phenomena can take an interdisciplinary program to develop depth in various areas. The advantage of this approach is that the interrelation between the physical, chemical and catalytic concepts is made at the outset, thereby providing the necessary continuity. Furthermore, this course would give a catalysis-related point of view into surface interactions for students from such areas as solid state physics, chemistry and material science. What follows is a suggestion for the scope and organization of such a course (based on a new course in development at the University of Wisconsin). In addition, the relationship of this course to the University of Wisconsin curriculum in chemical reaction engineering is shown in Figure 1. As limiting cases, reaction engineering is divided into (1) reactor engineering and design, and (2) catalysis and catalyst design, since these are the two major areas of specialization within this field.

COURSE SCOPE

IN CONTEMPORARY SURFACE science and catalysis research, there appears to be a gap between developments in fundamental theories of adsorption for simple species (e.g. H, CO), and

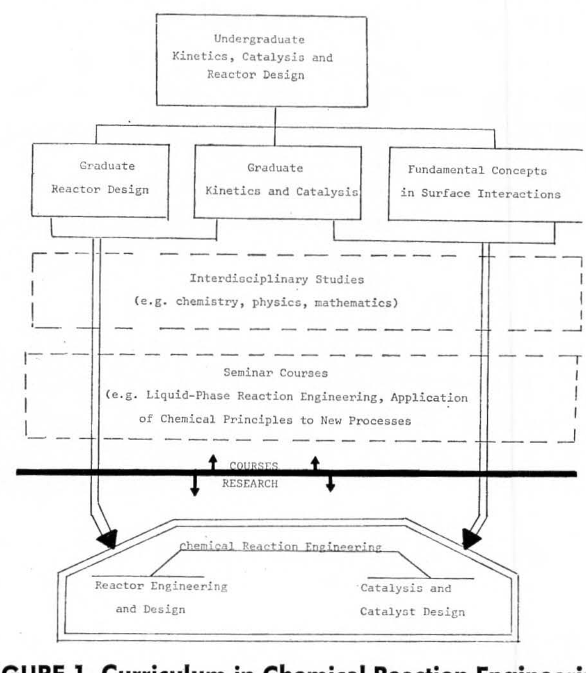

FIGURE 1. Curriculum in Chemical Reaction Engineering.

interpretations of reaction kinetics and adsorption behavior for catalytically interesting species (e.g. hydrocarbons). This gap arises primarily from the difficulty (computational, not fundamental) in treating "complex" adsorbed species rigorously in the framework of the adsorption theories. Yet, it seems reasonable (from both a research and educational point of view) to develop and use the concepts of the theories qualitatively (for now) to aid in the understanding of these "complex" adsorption and reaction phenomena. This is, in fact, a major objective of the suggested course.

The least that one must expect of a qualitative theory of adsorption phenomena is that it be consistent with the symmetry of the (absorbed species—surface) system. Furthermore, it seems reasonable to exhaust those concepts derivable from symmetry alone (since this can be done rigorously) before construction of a qualitative theory. Therefore, the first part of the course deals with group theory, and its application to surface and chemical phenomena.

Before considering detailed calculations of the electronic structure of the (absorbed species—surface) system, it is convenient to treat the adsorbed species and the solid at infinite relative separation. That is, the next phase of the course introduces molecular orbital theory and solid state physics, respectively. Subsequently, the absorbed species is allowed to interact with the surface, leading to chemisorption.

In the final part of the course, the theoretical concepts are applied to various topics in adsorption and catalysis. This demonstrates how the general theory can be simplified to obtain meaningful results for different types of catalysts and reactions.

COURSE STRUCTURE

THE OVERALL STRUCTURE of the course is schematically shown in Figure 2, and it is seen therein that there are four major divisions: symmetry, solid state, surface interactions, and applications to adsorption and catalysis. These are discussed in greater detail below.

1. Symmetry

One begins with the concept of symmetry operations (e.g. proper rotations, mirrors), and the classification of molecular structure in terms of point group symmetries. For a given point group, representations for the group and the bases for these representations are then considered. Through appropriate manipulation, each representation can be decomposed into a set of irreducible representations; this leads to the character table for the group. With a minimum of abstract derivation, group theory can be applied to chemical phenomena; indeed, the different applications result primarily from different choices of basis. These applications include: (1) infrared and Raman spectroscopies, (2) crystal field theory, (3) hybridization, (4) ligand field theory, (6) the Woodward-Hoffmann rules, and importantly (7) molecular orbital theory.

Along with the above applications, one must introduce the concept of matrix elements of operators, since symmetry can be used to deduce

There appears to be a gap between developments in fundamental theories of adsorption for simple species (e.g. H, CO), and interpretations of reaction kinetics and adsorption behavior for catalytically interesting species (e.g., hydrocarbons).

when various matrix elements must be identically zero. Then it is shown that two states may "interact" with each other when matrix elements between them are nonzero; depending on the symmetry of the interaction operator (e.g. the Hamiltonian) this imposes restrictions on the symmetry of interacting states.

When translation is added to the point group symmetry operations, then the two- and three-dimensional space groups are generated. Special sites in the unit cell are classified according to their point group symmetries; for the two-dimensional space groups, these sites become adsorption sites on surfaces. However, the most striking consequence of the translational symmetry is diffraction. As examples, x-ray diffraction (three-dimensional) and/or low energy electron diffraction can be discussed. This leads naturally into the reciprocal lattice. When "external diffraction" is replaced by "internal electron diffraction," solid state electronic structure is introduced.

2. Solid State

After a brief review of the Schrödinger equation and its implications in atomic structure (i.e.

s-, p- and d-orbitals), the free electron gas model for simple metals is derived. In so doing, k-space (wavevector space) can be introduced, followed by the computation of the density of states from constant energy contours in k-space. The occupation of these states by the electrons is in accord with Fermi-Dirac statistics. Next, the effect of the periodic placement of the metal atoms is "turned on," leading to "internal electron diffraction." As discussed in the symmetry part of the course, diffraction can be described by the reciprocal lattice, and in this way k-space becomes divided into the Brillouin zones. Furthermore, the translational symmetry of the lattice requires that the electron wavefunctions be written as Bloch functions, and all Brillouin zones can then be diffracted (translated in k-space) back into one zone. This is the reduced zone scheme for display of band structure.

Through the free electron gas model the basic concepts of solid state physics have now been introduced. Next, these concepts are used to discuss qualitatively the electronic structure of semiconductors. Of particular importance are (1) doping of semiconductors (p- and n-type), (2) conduction electrons and valence holes, and (3) the bending of bands due to electron transfer.

Of special importance are transition metals and the associated d-band. Because the d-orbitals are not as diffuse as the outer valence s- and p-orbitals (e.g. 3d orbitals are less diffuse than 4s and 4p), the tight-binding approximation can be used to describe the d-band; on the other hand, the (nearly) free electron gas model seems adequate to describe the broader (in energy) s- and p-bands resulting from the valence s- and p-orbitals. Qualitatively, at least, the electronic structure of transition metals can now be simply represented.

Finally, the solid state portion of the course can be supplemented by a discussion of defects and defect reactions. An appropriate defect symbolism should be introduced (e.g. Kröger symbolism), allowing defect reactions to be written consistent with the material balance, charge balance and lattice site balance. Then problems in for example non-stoichiometry, disorder type, and controlled (through doping) valence and defect concentration can be addressed.

3. Surface Interactions

One is now ready to consider the interaction of adsorbed species with surfaces. To parallel the solid state section, one may begin with adsorption

I. SYMMETRY	II. SOLID STATE	III. SURFACE INTERACTIONS
Point Group Symmetry Representations/Bases Character Tables Applications IR/Raman Spectroscopies Crystal/Ligand Fields Woodward-Hoffmann rules Hybridization Molecular Orbital Theory Matrix Elements Orbital "Interactions" Space Group Symmetry Translation Diffraction Reciprocal Lattice	Free Electron Gas Density of States Fermi-Dirac Statistics Brillouin Zones Bloch Functions Semiconductors Conduction Electrons Valence Holes Doping (p and n) Transition Metals s, p, and d-bands Tight-Binding Defects Symbolism Balances	Semiconductors Boundary Layer Theory Cumulative Adsorption Depletive Adsorption Photocatalytic Effects "One-Dimensional Metal" Surface States Adatom Density of States Bonding/Antibonding States Surface Molecule Real Metals Green's Functions Level Width Function Level Shift Function Surface bands Symmetry of Adsorption
IV. APPLICATIONS TO ADSORPTION AND CATALYSIS		

FIGURE 2. Structure of the Course: Fundamental Concepts in Surface Interactions.

on semiconductors. Starting with boundary layer theory one again encounters bending of the electron bands due to charge transfer at the surface. This leads to the cases of cumulative and depletive adsorption. As a more advanced example, one may discuss photoadsorptive and photocatalytic effects in semiconductor catalysis.

For adsorption on metals, a one-dimensional model can be used to illustrate many of the physical principles pertinent to adsorption on real surfaces. Specifically, a semi-infinite chain of atoms is modelled in the tight-binding approximation to form a one-dimensional d-band. Of significance, is the density of states on the surface atom, and in certain cases a localized surface state is formed (i.e., the electron density of this state decays exponentially from the surface into the bulk). Then, an adatom is allowed to "adsorb" on the surface end of the chain, and one calculates the adatom density of states. For a sufficiently strong interaction between the adatom and the surface, localized bonding and antibonding states are formed, leading to the concept of a surface molecule.

The treatment of adsorption on two-dimensional surfaces is facilitated by introduction of the Green's function. It then follows that the metal and adatom density of states (for the interacting system of adatom plus metal) are readily derivable from the Green's function. In particular, the adatom density of states can be written in terms of a level width function and a level shift function. Then, in order to bring together all aspects of the course: (1) a surface d-band is constructed in the tight-binding approximation (solid state), (2) matrix elements between the absorbed species molecular orbitals and the surface d-band are inspected (symmetry), and (3) the adatom density of states is analysed (surface interactions).

4. Applications

The course ends with the application of these fundamental concepts to topics in adsorption and catalysis. This can be done through formal lectures or student special projects and reports. The latter procedure was followed at the University of Wisconsin, and below is a list of special projects recently chosen by students.

Application of Woodward-Hoffmann rules to catalysis
Alloy catalysis
Electronic properties of metal clusters
Electronic and structural factors for adsorption on semiconductors
Surface diffusion in catalysis
Absorbed atomic species (oxygen on metal oxides)
Statistical mechanics of adsorption
Hydrogen adsorption on metals.

CONCLUDING REMARK

The primary objective of the course is to provide the physical and chemical breadth that is necessary for a fundamental understanding of adsorption and catalytic phenomena. As a result, a significant fraction (ca. 30%) of the course enrollment at the University of Wisconsin has come from students in physics, chemistry and material science.

In the course, basic concepts pertinent to surface interactions are introduced and synthesized in various simple applications. The necessary proficiency in the use of the concepts for the interpretation of reaction kinetics and adsorption phenomena comes with further practice and study. This can be accomplished by subsequently following an interdisciplinary program of course study, and/or reading the literature. □

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A Course in

ELECTROCHEMICAL ENGINEERING

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"If a piece of zinc and a piece of copper be brought in contact with each other, they will form a weak electrical combination, of which the zinc will be positive, the copper negative. This may be learned by the use of a delicate condensing electrometer, or by pouring zinc filings through holes in a plate of copper upon a common electrometer; but the power of the combination may be most distinctly exhibited in the experiments, called Galvanic experiments, by connecting the two metals, which must be in contact with each other, with a nerve and muscle in the limb of an animal recently deprived of life, a frog for instance; at the moment the contact is completed, or the circuit made, one metal touching the muscle, the other the nerve, violent contractions of the limb will be occasioned."

—Humphrey Davy, 1812, in Elements of Chemical Philosophy, London: J. Johnson and Company.

THE AMERICAN INSTITUTE of Chemical Engineers was founded in 1908 in response to the growing industrial interest in electrochemical processes such as chlorine, caustic, carborundum and electroplating of copper and nickel. Electrochemical engineering is therefore no stranger to the main stream of chemical engineering and is taught presently in many leading American universities.

The primary objective of an electrochemical engineer as well as of every chemical engineer is to bring chemical processes to practical realization and to operate them under optimal and economical conditions. Electrochemical engineering serves electrochemistry in the same way that ChE interacts with chemistry.

Electrochemistry is the science which studies the direct conversion between electricity and chemical reactions. It is the oldest branch of physical chemistry and can be traced back to the eighteenth century. There is even evidence of the use of primitive batteries in antiquity. Ancient iron-copper batteries were found in Iraq and evidence of copper electroplating was found in Egypt. Modern electrochemistry emerged from the pioneering discoveries of Volta, Galvani, Davy and Faraday in the early nineteenth century.

Electrochemical engineering is a relatively young field, which emerged in the beginning of the twentieth century, and progressed rapidly in the last thirty years with the expansion of the electrochemical industry. Electrochemistry played an important part in the scientific and technological revolution of the twentieth century. Thomas Edison can best be described as an electrochemical engineer. His original laboratory, presently preserved in Greenfield Village near Detroit, is a classical example of an electrochemical laboratory.

Today the electrochemical industry consumes nearly 10% of the total electrical power generated in the United States. Many of the things taken for granted in the pleasures and necessities of modern living depend on electrochemistry. Few people are aware of its role and importance. The most recognizable example is the battery. In the form of dry cells, storage batteries and fuel cells electrochemistry provides the power for many devices. From the tiny batteries of calculators, radio transistors and implanted heart pacemakers to the

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On the faculty of Wayne State University since 1972, Jacob Jorne has developed a research program in electrochemical engineering which includes the fundamental studies of the zinc-chlorine battery, hydrogen fuel cells, nonaqueous electrochemistry, solar electrochemical conversion and corrosion. He is consulting to various electrochemical industries. He is currently engaged in studying both theoretically and experimentally the role of population diffusion and dispersion in ecological systems, and the stability of prey-predator interacting populations.

large fuel cells of the Gemini and Apollo space flights, electrochemical energy conversion is the only known way to convert and store electrical energy directly.

Synthesis of essential chemicals can only be accomplished by electrolysis. Most of the important metals are produced, or the impure form refined, exclusively by electrolysis. All the aluminum, magnesium and nickel and a large portion of the copper and zinc are produced or purified in hundreds of thousands of tons per year by electrochemical processes. The aluminum production processes alone consume a staggering 72 billion KWhr annually. Chlorine, which is an extremely important raw material in the plastic industry, is produced electrochemically in the amount of several thousand tons per day. Any improvement in the current efficiency and overpotential of these processes is of utmost importance. Plating, electrochemical machining of hard metals and desalination of sea water are all examples of electrochemical processes which are conducted on remarkably large scales throughout the world.

All of these processes have one principle in common. They all depend on a chemical process taking place at an electrically conducting surface while simultaneously giving up or taking on one or more electrons. Energy for the reaction comes from pumping electrons into the reaction zone.

The emergence of electrochemical engineering as an independent field is quite similar to that of ChE. Both fields introduced the concept of transport phenomena, especially mass transport, and quantitative approaches. The importance of convective diffusion in electrochemical systems is due to their heterogeneous nature. Nernst introduced in 1904 the concept of the film model which is no more than a simplified stagnant diffusion boundary layer. However, the importance of mass transfer in electrochemical systems was fully recognized from the original works of Benjamin Levich, Carl Wagner and Charles Kasper in the 1940's; this was later developed into a recognized academic program by Charles Tobias and John Newman.

Today electrochemical engineering is an integral part of ChE and is taught in many ChE programs in major American universities among them: U.C. Berkeley, U.C. Davis, U.C.L.A., Illinois, Case Western Reserve, Illinois Institute of Technology, Northwestern, Connecticut, Oregon State, Michigan, Wisconsin and Wayne State.

Electrochemical engineering is not limited to the subject of transport phenomena. The main stream of research includes energy conversion and storage (batteries and fuel cells); scaling up; current distribution, porous electrodes, organic electrochemistry, photo-electrochemistry and the utilization of solar energy, non-aqueous electrolytic solution and molten salts, electromachining and environmental aspects among others. The central problems of electrochemical engineering are to increase the productivity of electrochemical reactors and to improve their energy efficiency.

The heart of the course is dedicated to the various overpotentials and evaluating of cell potential scaling up and design consideration of electrochemical reactors.

Electrochemical systems are very complex and their principles depend upon the understanding of thermodynamics, kinetics, transport phenomena, electricity and surface phenomena. Though we have not yet arrived at a point where all can be left to the computer, perhaps the electrochemical industry is now emerging from an era of empiricism and becoming more quantiative.

COURSE DESCRIPTION

AT WAYNE STATE University a three hour credit course in electrochemical engineering is offered annually during the Winter quarter. The course has been taught since 1973 and was attended by approximately sixty students, both graduate and seniors. The course is open to engineers and chemists from the local Detroit industry and is scheduled every other year during the evening hours to enable part-time students and professionals to attend classes. The electrochemical engineering course is followed by a corrosion course in the Spring quarter.

The course does not follow a particular textbook, but rather a set of notes and homework problems. A list of recommended books is given in the reference section. The homework problems are assigned weekly and the final grade is determined by two exams and a term paper. The students usually select the subject of the termpaper from a list of topics. The course outline is presented in Table 1 and a list of termpapers from

TABLE I. Electrochemical Engineering Course Outline

1. Introduction to Electrochemical Engineering
   a. The Scope and Importance of Electrochemistry
   b. The five "E": Electrochemistry, Engineering, Energy, Environment and Economics.
   c. Examples from the Electrochemical Industry
2. Faraday's Laws
3. The Electrolytic Solution
   a. Conduction in Aqueous Solution—Debye-Huckel Theory
   b. The Concept of Electrical Potential
   c. Conduction in Nonaqueous Solutions and Fused Salts
   d. Primary Current Distribution in Various Geometrical Cells
4. Thermodynamics of Galvanic Cells
   a. The Electromotive Force
   b. Standard Potentials and the Nernst Equation
   c. Application of Electrochemical Cells: Measurements of Gibbs Free Energy, Entropy, Enthalpy, Activity Coefficients, Standard Potentials and Sign Convention
   d. Reference Electrodes
5. Electrochemical Kinetics
   a. The Electrical Double Layer
   b. The Theory of Rate Processes Applied to Electrochemistry
   c. The Tafel Equation
   d. Charge Transfer Overpotential
6. Mass Transfer in Electrochemical Systems
   a. Diffusion Controlled Electrochemical Reaction
   b. The Importance of Convection and the Concept of Limiting current
   c. Mass Transfer Overpotential or Concentration Polarization
   d. Secondary Current Distribution
   e. The Rotating Disk Electrode
7. Synthesis of the Principles and Applications
   a. Evaluation of Cell Potential and Overpotential
   b. The Combined Effect of Standard Potential, Ohmic Resistance, Charge Transfer and Mass Transfer Overpotentials
   c. Industrial Examples: Batteries, Chlor-Alkali Industry, Aluminum Production, Copper Refining, Plating, Electrowinning, Corrosion
   d. Modeling and Optimization of Electrochemical Systems
   e. Electrochemical Machining-Design Problem
   f. The Chlor-Alkali Industry-Economical and Environmental Evaluation, New Process Design
8. Students Presentation of Term Papers. See Table II for examples

the last several years is presented in Table 2. The course is not intended to cover the physical chemistry of electrolytic solutions or the principles of electrochemistry, however many ChE students have not studied enough electrochemistry in their physical chemistry sequence. Consequently the first three weeks are devoted to the survey of Faraday's laws, ionization and electrolytic solutions, the standard potential and the Nernst equation. This is done in order to bring all the students to the same level.

The heart of the course is dedicated to the various over-potentials and evaluation of cell potential, scaling up and design consideration of electrochemical reactors.

The convenience of using electrochemical techniques in mass transfer measurements is emphasized: the rate (current) and the driving force (potential) can be easily controlled and measured. However the complications due to electrical migration and non-uniform current distribution are brought to the class attention. The concept of mass transfer limiting current i_L is introduced and the ChE students are reacquainted with this electrochemical term which is directly related to the familiar Sherwood number

$$Sh = i_L \cdot L / n \cdot F \cdot D \cdot C_b$$

where F is the Faraday's constant, n the number of electrons transferred in the electrochemical reaction, D is the diffusion coefficient, L the characteristic length, and C_b is the bulk concentration. Measuring the limiting current is therefore an easy way of establishing mass transfer correlations.

TABLE II. Examples of Term Papers

1. Developmental Batteries For Electric Vehicles
2. Bioelectrochemistry of Membranes and Nerves
3. Ion Selective Electrodes
4. Decorative Electrodeposition: Copper, Nickel, Chrome Plating
5. Feasibility of Making Cl_2 and NaOH at Very High Current Densities
6. Signal Transmissions in the Nerves
7. Energy Efficiency in Aluminum Production
8. Rotating Disk and Ring-Disk Electrodes
9. Pitting Corrosion—Electrochemical Aspects
10. Fuel Cells
11. Intermolecular Potentials and the Kinetics of Ionic Solutions
12. Cathodic and Anodic Protections.
13. Electrochemical and Photochemical Responses in the Eye
14. Low Pressure, Low Temperature Hydrogen—Oxygen Fuel Cells
15. The Chlor-Alkali Industry
16. The Use of Dimensionless Groups in Electrochemical Engineering
17. Electrochemical Machining
18. The Hydrogen Economy: Water Electrolysis and Fuel Cells.

The last section of the course is devoted to applications, especially energy storage and conversion and various important electrochemical processes, e.g. the chlor-alkali industry, aluminum production and the proposed hydrogen economy. Special topics of interest include bioelectrochemistry, membranes, electrodialysis, electrochemical machining, porous electrodes and high energy batteries.

An interesting class project is the technical comparison and economical evaluation of the various processes for chlorine-caustic production: the mercury, diaphragm and the newly developed membrane cells. The environmental impacts of the three processes are discussed at length. A new high current chlorine production process which involves high flow velocities is proposed as an exercise and the students are asked to design the process and to compare it to existing processes.

The novel technique of electrochemical machining is brought as an example of achieving very high rates which were unheard of only 15 years ago. In this technique the negative replica of the cathode is reproduced in the anode piece by high rate anodic dissolution. High current densities in the order of 100 A/cm^2 can be achieved by circulating the electrolyte at high velocities (10 m/s) through a very small gap (0.1-0.5mm). This is an excellent example of incorporating ChE and electrochemistry principles. The students are asked to design an electrochemical machining system using well known heat, mass and momentum transfer correlations, and to evaluate the power consumption.

CONCLUDING REMARKS

INDUSTRIAL ELECTROCHEMICAL processes will no doubt increase in relative importance to other chemical processes in the future. Increasing electrical energy generation relative to petroleum production will favor electrochemical processes and will need new electrochemical storage and conversion methods. Many known electrochemical reactions will be re-examined and improved. New membranes and new electrodes will be developed, and electro-organic chemistry as well as metal production by electrowinning will be expanded. It is anticipated that careful application of electrochemistry to biological problems will provide new solutions and new techniques. It is predicted that biological membrane research will expand. Direct application of electrochemistry to therapeutic situations will increase in the medical profession.

The role of the electrochemical engineer of the future will be to bridge the gap between the scientific discoveries and the yet unkown economic reality of the future. The present trend in electrochemical engineering of better quantitative understanding, better cell design, scale up and optimization insure that we are ready to fulfill the promising future of electrochemistry. □

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ChE book reviews

INTRODUCTION TO MATERIALS SCIENCE (SI EDITION)

by B. R. Schlenker
John Wiley & Sons Australiana Pty, 1974.
364 pages.

Reviewed by C. E. Birchenall, U. of Delaware

In the foreword to this book, Professor Hugh Muir cites the need for all sorts of people to develop a better feeling for material properties and their efficient utilization as justification for introducing materials science into high school curricula. The author chose the contents to match the New South Wales syllabus for one of the four parts of an industrial arts curriculum. The result is a descriptive survey of the wide variety of materials employed in engineering, with fitting emphasis on structure-properties relationships and

Continued on page 175.

A Course in

CHEMICAL REACTION ENGINEERING SCIENCE

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THE FOCUS OF the Chemical Reaction Engineering Science course at the University of Missouri-Columbia is on the theoretical description and interpretation of the phenomenological behavior of heterogenous catalysts. A student entering this course is presumed to have had at least a three hour course on chemical reaction engineering which covered the following topics:

1) Rate equations for homogenous reactions
2) Isothermal and temperature effects in the ideal batch, ideal plug flow, and the ideal stirred tank reactors
3) Characterization of non-ideal reactor performance by means of the residence time distribution, the dispersion model, the segregated flow model, and the tanks in series model
4) Heterogenous reactions and
5) Fluidized bed reactors. The course begins with a brief review of the batch, plug flow, and stirred tank reactors using a unified approach via the general material and energy balances expressed in terms of differential forms [1], i.e.—

$L_v A = f$	Navier Stokes Equation
$i(v)\, L_v A = i(v)\, f$	Energy Equation
$dJ = 0$	Conservation of Mass Equations

The stability analysis and existence of bifurcation points for the nonlinear isothermal and adiabatic operation of the ideal reactors is made using the degree of a map and surface curvature concepts in the differential form language. The solutions for these nonlinear problems is developed using Green's function techniques. This approach has the advantage of introducing at the beginning of the course the general mathematical and physical framework needed to analyze phenomenological catalytic behavior.

At this point in the course the Langmuir-Hinshelwood [2] description of fluid-solid catalytic reactions is developed. The approach taken is to first consider the situation in which one step (mass transfer, adsorption, surface reaction, pore diffusion or, desorption) is controlling the overall reaction rate. The equations appropriate to each case are developed. Mass and heat transfer correlations are discussed where needed. When pore diffusion is taken up both the Thiele modulus and the effectiveness factor are defined. Various geometric shapes of the catalyst as well as temperature gradients within the porous catalyst are dealt with. Multiple controlling steps in the reaction process are then reviewed and the appropriate design equations obtained. The uniqueness and stability of the various descriptions of catalyst behavior are analyzed using the mathematical tools

The stability analysis and existence of bifurcation points for the nonlinear isothermal and adiabatic operation of the ideal reactors is made using the degree of a map and surface curvature concepts in the differential form language.

previously presented. Current papers in the catalytic literature where these methods are used is reviewed. It is pointed out at this juncture that the Langmuir-Hinshelwood approach does not in general lead to a unique physical interpretation of the experimental data but generally provides adequate design equations.

FURTHER INSIGHT

TO FURTHER DEVELOP an insight into the physical process that occur during catalysis four final topics are considered in this course. They are: (1) geometric theory of catalysis, (2) the electron band theory of catalysis deals with

Continued on page 189.

If your middle name is impatience,

maybe we can put things on a first name basis.

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A Course in

BIOCHEMICAL ENGINEERING

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THE BIOCHEMICAL ENGINEER is primarily concerned with research, development, design, construction and operation of processes involving biological material. Current examples of these processes include the production of antibiotics, drugs, organic acids, foods, animal feeds, and biological waste water pollution control.

Future activities include the possibility of single cell protein production from unusual sources (hydrocarbons, cellulosic materials), glucose production from paper wastes, and microbial oil recovery. The one semester (3 credits) course offered in the graduate program at the ChE Department at the University of Delaware serves two purposes; to introduce the student rigorously to microbial and enzyme kinetics, mass transfer and biochemical processing, and secondly to develop the skills necessary to analyze and design fermentation systems, taking into account downstream processing constraints. The course is open to advanced seniors and graduate students.

Biochemical engineering is interdisciplinary and draws from many areas, but most strongly from microbiology, biochemistry and chemical engineering. There are major hurdles to overcome in providing training for students coming from one of these areas in the other two. This course is taught to ChE students and provides them with the skills necessary in the other two areas. No attempts have been made to offer the course to non-engineering majors, as it is based on a strong background in kinetics, fluid mechanics and mass transfer. The course is available to civil engineering graduate students in environmental engineering. Table I shows an outline of the topics and lectures. A design project is introduced after the section on mass transfer and class time is allocated periodically to review problems arising in

TABLE I. Introduction and Scope of Biochemical Engineering

Fundamentals of Biochemistry and Microbiology
Microbial taxonomy, growth requirements of microorganisms, carbohydrate and lipid metabolism; electron transport, replication and genetics

Kinetics of Microbial Growth
Constitutive expressions for growth, structured and unstructured models, substrate inhibition, kinetics of product formation, influence of the external environment

Batch and Continuous Culture
Mass balances for batch, CFSTR, tubular and multivessel systems, the turbidostat, stability of reaction, dynamics, equipment for batch and continuous cultures, computer coupled fermentations

Mass Transfer
Fundamentals of two phase gas/liquid mass transfer, predictions of $k_L a$, aeration and agitation systems, airlift fermenters, novel devices, power requirements for agitation, scale-up, non-Newtonian systems, microbial film fermenters

Reactor Design
Design of tank type and tubular biochemical reacting systems

Process Design
Influences of downstream processing constraints on process design (extraction, filtration), medium sterilization, air sterilization.

Mixed Microbial Cultures
Interactions between microorganisms, predator-prey interactions, stability of mixed cultures, applications

Enzyme Engineering
Kinetics of single and multiple enzymes in solution, enzyme reactors, immobilized enzymes, supports and couplings, kinetics of immobilized enzyme reactors, applications

Industrial Processes
Design project, biological wastewater treatment, detailed analysis of a complete fermentation plant, sterilization of medium, product extraction

the design. The design familiarizes the students with the problems of scale-up of fermentations, and the difficulties of sterile operation. Final designs are presented orally at the conclusion of the course.

A section on the fundamentals of microbiology and biochemistry introduces the various types of microorganisms encountered and their composition. Much of the material is taken from Aiba, Humphrey, Millis [1], supplemented with references to introductory microbiology texts. Carbohydrate metabolism is examined using material from Conn and Stumpf [2] and Aiba et al [1]. Anaerobic and aerobic pathways common to important fermentation products are covered, and lipid metabolism and secondary metabolite pathways reviewed. The reproductive cycles of bacteria, viruses and fungi are described, and the importance of mutation as a tool for increasing product yields is emphasized. This comprises 8 hours of lectures.

MICROBIAL GROWTH KINETICS

THE DEVELOPMENT OF constitutive kinetic rate expressions for microbial growth comprises three hours of course time. Unstructured models, such as the Monod relationship, are developed, and concepts of endogenous metabolism, cell yield, models for product formation and substrate inhibition introduced. The analogy between constitutive expressions in chemical reacting systems and those in microbial systems is emphasized. In this way batch, chemostat and turbidsotat systems are introduced in a natural fashion. The distinction between the rate expression, being experimentally determined, and component mass balances around the system, is not always clear in the literature, especially that of waste water and sanitary engineering. An article by Fredrickson et al [3] overviews both unstructured and structured models, and the concepts of balanced and unbalanced growth follow logically from an examination of structured models. The influence of external parameters, such as type of substrate, temperature and pH is emphasized.

There are several specific examples in which unexpected results emerge from the coupling of microbiological processes and reactor control. In one it is shown that feedforward proportional derivative control of recycle sludge into an activated sludge sewage treatment process, for variations in incoming waste flow, results in control of the effluent waste carbon concentration, this being independent of the expression used to describe the specific waste utilization rate.

Using the previously developed rate expressions, organism, substrate and product balance equations are simply developed for a variety of reactor configurations. The effect of various operational parameters is investigated by solving the algebraic or differential mass balance equations using a simulation language on the digital computer. Both MIMIC and CSMP have useful built-in plotting routines. This also allows a simple numerical investigation of the stability of various configurations (e.g. cell recycle) and rate expressions; this supplements the analytical investigation of system stability to small perturbations. Systems dynamics and various control strategies can be easily introduced and modeled. The approach is outlined in a review article [4].

The equipment required to monitor and control fermentation systems is unique to the chemical process industry in some respects, and important problems are discussed (e.g. the requirements of sterile operation, inoculum preparation, pH and dissolved O_2 probes). The newly developing area of computer-coupled fermentations is emphasized. Aiba et al [1] and Nyiri [5] provide useful background. Computer-coupled fermenters are reexamined following the section on mass transfer, including paramters such as k_La, apparent viscosity and rate of heat evolution.

There are several specific examples in which unexpected results emerge from the coupling of microbiological processes and reactor control. In one it is shown that feedforward proportional-derivative control of recycle sludge into an activated sludge sewage treatment process, for variations in incoming waste flow, results in control of the effluent waste carbon concentration, this being independent of the expression used to describe the specific waste utilization rate. This has obvious implications in the overall control of wastewater treatment plants.

MASS TRANSFER

THIS SECTION COMPRISES 10 lectures and assumes an understanding of undergraduate heat and mass transfer. Two phase gas-liquid reactor design equations are developed for tank type reactors, using the "ideal" reactor concept. Plug-flow gas and well-mixed liquid phases and both phases well-mixed are considered. The material for this section is based on a series of articles by Russell [6-8], which emphasize design, based upon the fundamentals of fluid mechanics and mass transfer. The parameters which must then be evaluated follow naturally. Tubular systems are briefly reviewed. This provides a rational basis for considering the problems of scale-up. The available data for estimating interfacial area a and the mass transfer coefficient k_L are discussed, based on Russell [6], and various correlations for k_La from the literature are reviewed [9]. The transition from Newtonian to non-Newtonian fermentation broths introduces the student to the complexities of real systems. The power requirements necessary to obtain the desired degree of mass transfer in both stirred tank and air-lift fermentors are examined, as are mixing times and shear rates. This then leads into a discussion on bases for scale-up, and novel fermentation devices.

DESIGN PROBLEM

UPON COMPLETION of the section on mass transfer and scale-up, the class is presented with a design problem, to be tackled in groups. The problem is given only in simple terms, e.g., to design a plant to produce 300 trillion units of penicillin per year. The prime thrust is to obtain suitable reactor configurations, mode of operation, and sufficient oxygen transfer capabilities. Somewhat less time is spent in medium sterilization and extraction. The design serves to further familiarize the student with the literature and provide an introduction to some of the differences between pharmaceutical and traditional chemical process industries. Longer holding times for example, are typical of most microbial systems. Other designs, emphasizing the two-phase nature of the problem, may include biological wastewater facilities (see, for example, Atkinson [10]. In the usual senior design project, typically not a great deal of attention is paid to mixing and gas-liquid mass transfer in stirred tank devices, so the material covered in this section will, in general, supplement the senior design course. The last week of the semester is spent reviewing designs and discussing an actual complex fermentation plant.

Although not a great deal of consideration in the past has been given to mixed cultures, their importance is becoming more apparent. The various types of interactions between microorganisms can serve as a rather unique model system for other interacting ecosystems, in which energy is transferred from lower to higher trophic levels. Predatorprey interactions are analyzed in some detail, and the stability of various systems is examined. The existence of experimentally observable limit cycles in a protozoan-bacterium system provides an interesting introduction to the vast literature on oscillations of populations of higher organisms. May's monograph [11] serves as a source for many of these references, and provides a readable discussion of limit cycles on a fairly elementary level.

The one semester (3 credits) course serves two purposes: to introduce the student rigorously to microbial and enzyme kinetics, mass transfer and biochemical processing, and secondly to develop the skills necessary to analyze and design fermentation systems, taking into account downstream processing constraints.

ENZYME ENGINEERING

IN A COURSE SUCH as this, it is difficult to spend as much time as one would like on various areas, and enzyme kinetics and enzyme engineering can only be fairly superficially covered. The behavior of single and multiple enzymes in solution is reviewed and the problems of diffusion and reaction in immobilized enzyme systems discussed. Experimental methods of immobilization, are reviewed, including how these methods may alter the observed kinetics. Various reactor configurations and applications are discussed. Atkinson [10] and Aiba et al [1] serve as reference sources, and the student is given homework problems which direct him to the already vast literature here.

The course aims to present a rigorous and formal introduction to biochemical engineering, emphasizing the students' ChE background. Analogies are drawn with reaction kinetics, heat and mass transfer, and design learned at the undergraduate level. The student is provided with the elementary tools in biochemistry and microbiology, and a familiarity with current views and literature in these areas. Clearly further coursework in applied microbiology or biochemistry is required for those students doing graduate work in the area, and this is usually a component of the graduate coursework for M.S. and Ph.D. candidates. Thoroughout the course homework problems are assigned to supplement the lecture material. As there is no convenient text source of problems, some of these are taken from fairly recent literature articles. This helps to emphasize the quantitative rather than descriptive nature of the area. □

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ENGLISH OR TECHLISH: Van Ness & Abbott

Continued from page 159.

- **The second sentence says that finding a velocity assures a packed-bed system. Nonsense.**
- **Not afraid of the first person, the author over-does a good thing; "Our fluidization velocity" is inappropriately personal.**

Two final quotations and their translations illustrate several of the points made earlier.

Techlish: *To attain this area the heat exchanger contains 100 9 foot long pipes with an inner diameter of one inch.*

English: *A heat exchanger with 100 9-foot-long, 1-inch-i.d. pipes provides the required area.*

Techlish: *The shale preheater has a feed of raw shale supplied to it between 60-90°F which is to be heated to 600°F and then fed into the reactor. The exchanger is to utilize exhaust gas from the reactor as its heat transfer fluid.*

English: *Before entering the reactor, raw shale is preheated from about 60°F to 600°F. Exhaust gas from the reactor serves as the heat-exchange fluid.*

The "shale preheater" of the second quotation comes as a surprise; we would have expected steel or perhaps cast iron.

Writing good technical prose is a difficult task; few persons can do it easily or quickly. A first draft is usually in need of substantial revision; several rewritings are normally required. Some expert help is provided by a good dictionary, which should be consulted frequently for the proper meanings (and spellings) of words. Especially useful is a little book, called "The Elements of Style", by William Strunk, Jr. and E. B. White. The second edition of this book, published by Macmillan, is printed in paper-back at under $2.00. In 78 pages the authors say all that need be said on the subject. Every engineer should keep a copy at hand.

Rather than supply our own ending to this piece, we offer the closing words of a student report:

> *Due to the small choice of alternatives related to this study, the complexity of our conclusions remain at a minimum. In conclusion it is readily apparent that further research would definitely pay off in the form of further insight into this problem.*

Who could disagree? □

POLYMER SCIENCE AND ENGINEERING

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THE PRIMARY responsibility for the Polymer Science and Engineering graduate course program at the University of Cincinnati rests on four faculty members: Professors F. J. Boerio and R. J. Roe of the Department of Materials Science and Metallurgical Engineering, Professor R. P. Chartoff of the Department of Chemical and Nuclear Engineering and Professor J. E. Mark of the Department of Chemistry. When an incoming graduate student, enrolled in any one of these departments, expresses the desire to pursue polymer specialization, he or she is advised to take a series of four one-quarter core courses offered by the four faculty members. According to the offering sequence, these are: "Introduction to Polymer Science" taught by F. J. Boerio, "Physical Properties of Polymeric Materials" by R. J. Roe, "Polymer Configurations and Rubber-like Elasticity" by J. E. Mark and "Polymer Engineering" by R.P. Chartoff. These four courses are designed to acquaint the students, in an orderly sequence, with fundamentals of most major aspects in polymer science and engineering including preparation, characterization, structure, properties and processing. Descriptions of the courses are listed in Table 1. Topic coverage and the sequence of offerings in all of the courses is closely coordinated among the cooperating faculty members.

Through the experiments students are given opportunities to become thoroughly familiar with the various types of instrumentation likely to be found in any industrial or academic polymer laboratory

The lecture courses are augmented by two one-quarter laboratory course, "Polymer Characterization" and "Polymer Engineering Techniques" (see Table 1). All the four faculty members simultaneously participate in these two laboratory courses on a shared basis and offer a variety of experimental topics according to the areas of their expertise. From among 15 to 20 experimental topics offered in each laboratory, students are free to select any 8 according to their individual interests. Within the two quarter period a student can choose a series of lab experiences which provide a broad exposure to several different topic areas. At the same time those who wish to can narrow their selection to a minimum of different areas and concentrate more in depth on any one, such as polymerization or processing. The possibilities available for individual selection are illustrated in Figure 1. Since progress in polymer science and engineering heavily depend on experiment, the emphasis on laboratory experience for graduate students is a most essential part of the program. Through these experiments students are given opportunities to become thoroughly familiar

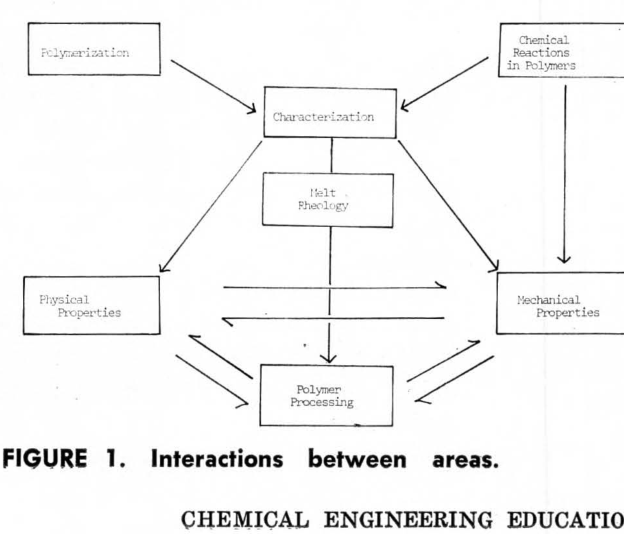

FIGURE 1. Interactions between areas.

with the various types of instrumentation likely to be found in any industrial or academic polymer laboratory. This is valuable for learning useful techniques for their thesis research and gives them an edge in obtaining future employment after they finish their graduate study.

After completing the sequence of basic courses, students are further encouraged to take other elective courses on specialized topics in polymers. These include "Transport Processes in Polymer Systems", "Organic Synthesis of Polymers", "Polymer Spectroscopy" and "Polymer Morphology".

The Polymer Science and Engineering program is a graduate program only at the present, but undergraduate students interested in polymers can become introduced to the basic aspects of polymer science through two elective courses "Polymeric Materials" and "Polymer Technology". The two laboratory courses mentioned above are also offered to advanced undergraduate students. □

TABLE 1. Graduate Polymer Courses

Introduction to Polymer Science **3 credits, Lecture,** Boerio, **Autumn**

Preparation and Characterization of polymers; addition and condensation, molecular weight averages and distributions.

Physical Properties of Polymeric Materials **3 credits, Lecture,** Roe, **Winter**

Solid state structure-property relationships in polymeric materials. The glass transition, structure of crystalline polymers, thermodynamics of polymer solutions and compatibility.

Polymer Configurations and Rubber-like Elasticity **3 credits, Lecture,** Mark, **Spring or Summer**

Configuration dependent properties and their interpretation; statistics of chain dimensions; network formation in crosslinked polymers; thermodynamics and mechanical properties of rubbers; statistical theories of rubber-like elasticity.

Polymer Engineering **3 credits, Lecture,** Chartoff, **Spring**

Fundamentals of polymer processing; design of processing operations and relation to physical and mechanical behavior in solid and molten states; viscometric measurements and melt elasticity; applied viscoelasticity.

Polymer Characterization **2 credits, Lab,** Boerio, Roe, Chartoff, Mark, **Winter**

Experimental investigations of structure and properties of polymers; molecular weight averages and distributions, thermal and mechanical properties, transitions, and crystallinity.

Polymer Engineering Techniques **2 credits, Lab,** Chartoff, Roe, Boerio, Mark, **Spring**

Measurements of viscoelastic properties, viscosity and flow parameters necessary for design of polymer processing equipment; relations between processing data and polymer molecular structure with applications to quality control.

Special Topics in Polymers **3 credits, Lecture, Staff, Winter or Spring**

Intensive coverage of specific topi csin polymer science and technology at a research level. To be offered irregularly three quarters in each two year period. Future topics will include polymer spectroscopy, transport phenomena in polymer systems, surface properties of polymers, organic synthesis of polymers, polymer spectroscopy, and polymer morphology. Offerings to be coordinated between Chemical Engineering, Materials Science, and Chemistry staff.

BOOK REVIEW: Schlenker

Continued from page 167.

brief summaries of methods of testing and characterization of materials, and the shaping and fabrication of objects. There are many illustrations, but they are not always intergrated with and explained in the text. Many experiments are suggested; some are self-explanatory, but others are not clear with respect to purpose, procedure or significance. An instructor is necessary to supply guidance—and to protect students and equipment. Some statements are inaccurate or misleading, but they are few and unemphasized among the multitude; not much damage is likely to result.

Professor Muir notes that, in spite of the title, the text is about the phenomenology of materials more than the principles and concepts of materials science. The few gestures toward a quantitative approach include a few mechanical testing equations and a statement of Bragg's law, together with the geometric figure customarily used in its derivation. The use of the lever rule is illustrated, but even this mass conservation principle, using only the simplest linear algebra, is not derived.

Should the study of materials be a part of high school curricula? Surely it is more exciting than bookkeeping, conveys more varied skills than typing, and is a valuable adjunct to shop practice or preparation for the building trades. This book would be a suitable text, although injection of a bit more of the formal structure of materials science might make the subject easier to retain. College-bound students should study science and mathematics in high school so they can learn materials science on a more systematic and quantitative level. □

EDITOR'S NOTE: The following papers deal with the rapidly developing graduate programs for students with a B.S. outside chemical engineering. The first paper is a general survey paper, the second discusses a specific program, and the third gives a student point of view.

ChE GRADUATE PROGRAMS FOR NON-CHEMICAL ENGINEERS

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WHEN TIMES ARE GOOD, college students tend to be interested in education. They study subjects because of inherent interest, without regard for the utility of what is learned. When times are unsettled, college students become much more interested in professional training. They believe that such professional education will facilitate employment. They often choose to study engineering because it provides one of the fastest routes to a professional degree.

Because times are currently unsettled, many students who have majored in chemistry as undergraduates are now interested in graduate study in chemical engineering. Most of these students have studied at private liberal arts colleges or at smaller campuses of state university systems. Those in the liberal arts colleges choose a more personal undergraduate experience. They are often undecided about a career or want additional time to mature. Those at the small state colleges are most commonly there because education is inexpensive. At both types of school, undergraduate engineering is rarely offered.

At the same time, many ChE graduate programs could use more qualified students. This is a consequence of the fact that there are more graduate programs than engineering student demand justifies. Many of these programs, which multiplied rampantly in the 1960's, have admitted huge numbers of foreign students to justify their existence. Independent of the foreign students' quality, many departments would prefer to enroll more North American natives. When departments see the supply of chemists available, the lure is obvious: why not teach ChE to chemists?

This essay explores the ways in which this teaching can be effectively accomplished. It explores what programs exist to do this, how they are operated, and how they can be started. In writing this essay, I have been strongly influenced by our own experiences. Our experiences and information are not exhaustive. Part of the reason is that there seem to be more programs for chemists than there are chemists in the programs, so that judging effectiveness is difficult. Another problem is that many seem reluctant to discuss efforts which have failed. In any case, before I start, I apologize in advance for not mentioning many specific experiences.

. . . we have not been able to find an effective text. The reason is that ChE is almost completely taught in a sequential fashion. As a consequence, we have had to write a text, which we would be glad to make available to others with similar problems.

OPEN ADMISSIONS

THE EDUCATION OF chemists as ChE's can be roughly organized into three methods. In the first method, one simply denies any difference. One admits chemists as engineers and has them take the same courses as engineering students. Such flexibility has a long tradition: almost every senior professor can remember a few individuals in the 1930's and 1940's who made such a transition. Moreover, it has the tremendous appeal of requiring little extra work, either by faculty or by the administration.

What is different now is the number of students involved. During the past few years, I have been surprised to discover that in a significant number of ChE departments, chemists make up the majority of North American graduate students. These departments have bright faculty, strong research support, and reasonable reputations. Since they seem to have operated successfully for at least five years, there may be no problem.

However, I am concerned about this method because I believe it significantly changes the education of the graduates. If more than a third of my graduate class is not trained in chemical engineering, the technical level of the material taught drops. Moreover, because the current trend in many departments is to reduce graduate course requirements, one may certify "engineering" graduates who know very little engineering. I should emphasize that I cannot either support or refute these opinions; I just feel concerned.

UNDERGRADUATE REMEDIAL WORK

THE COMMON ALTERNATIVE to open admissions is a program which requires undergraduate courses as part of the transition. While the number of courses varies considerably (cf. Table I), all include courses in transport phenomena, and most require thermodynamics. After completing these courses, the chemist enters the conventional graduate program. The cost to the university is minor, since no new courses are involved. Such requirements certainly insure a solid engineering education of both breadth and depth, so that graduates can be fully employed as chemical engineers. They are demanding; for example, in the Texas A&M program, only 25-30% of the students originally admitted qualify for graduate study.

The characteristic of this type of program is that it can have trouble attracting students. The chemists whom we want to attract are bright, aggressive, and individualistic. They often are admitted to medical school but cannot afford to go; they always are admitted to graduate school in chemistry with full fellowships. They cannot afford to undertake extensive remedial work at their own expense, which is the common expectation. As a result, many of these programs may attract only a small number of superior applicants.

We have preceded our special summer course with a one-week mathematics review, taught by people connected with our affirmative action program. This has two results: it provides the minority and returning student with the necessary mathematics and it also establishes firm friendships between these two groups.

SPECIAL COURSES

THE THIRD WAY of teaching ChE to chemists is to require special courses giving an accelerated synopsis of the undergraduate engineering curriculum. This is the strategy we have used here, and so is that with which I am most sympathetic. The effective development of this approach here has been facilitated by generous assistance from the Exxon Education Foundation. Such special courses require additional faculty and administrative effort at an approximate cost to date of $10,000/year. However, because of this accelerated synopsis, the quality of other graduate courses need not be compromised. Be-

TABLE I. Typical Remedial Programs

(All of these lead eventually to a masters degree)

University of Buffalo
Two courses in transport phenomena; one in unit operations.

University of California, Berkeley
Variable; for example, courses in thermodynamics, transport phenomena, kinetics, and design plus another elective.

Clarkson College
Courses in fluids, thermodynamics, heat and mass transfer, kinetics, control, and design.

University of Delaware
Courses in stoichiometry, thermodynamics, fluid mechanics, heat and mass transfer, kinetics, equilibrium stages, and design; seminar; laboratory.

Rensselaer Polytechnic Institute
Courses in kinetics, design, control, and mass transfer; some prerequisites in previous summer.

Rutgers University
Two courses in transport phenomena; one in design, and in mathematical methods; audit in control.

Texas A&M
Courses in thermodynamics, fluid mechanics, mass transfer, process control, kinetics, design, electrical engineering, and materials; laboratory.

cause of its speed, bright students with chemistry backgrounds quickly qualify for research support on government grants and contracts. Seventy percent of the students entering complete their degrees. The major difference is that the graduates are not conventional ChE's but a new breed, armed with a new mixture of skills. The implications are explored below.

As the above paragraphs describe, the educational innovation in programs for teaching ChE to chemists largely arises from the special courses designed to give a prompt synopsis of ChE (cf. Table II). As a result, these will be discussed in more detail. Although accelerated, the Texas Tech program is most similar to the remedial courses in Table I. It takes a full year, and consists of material taught at the same rate as the undergraduate courses of the same description. The chief difference is that the students in this course are separated from the conventionally trained engineers.

TABLE II. Accelerated Courses for Teaching Chemical Engineering

Carnegie-Mellon University

Eight week summer course covering the following sequentially: stoichiometry, thermodynamics, equilibrium stages, fluid mechanics, heat transfer, mass transfer; senior level design course required during the academic year, and kinetics often taken as an overload.

Texas Tech University

One year course equivalent to stoichiometry, thermodynamics, fluid mechanics, stages, heat and mass transfer, kinetics, economics, mathematics, design.

University of Virginia

Nine week summer program of two parallel courses consisting of 1) mathematics, fluid mechanics, and heat transfer; and 2) heat transfer, mass transfer, and kinetics.

The other two special courses, at Carnegie-Mellon and Virginia, consume about eight weeks of the summer before the masters year. They commonly have three hours of lecture per day, five days a week. They also have at least one problem-solving session every day. These problem sessions can run a long time. I had one at Carnegie-Mellon that started at 3:00 p.m. and continued until midnight. In our program, tutors are available both in the afternoon and in the evening. These tutors are largely graduate students whose backgrounds are in chemistry and who have already successfully completed the masters program. We rarely assign individual tutors to specific students.

The content of these two special courses is obviously a synopsis of undergraduate ChE. The students joke that the freshman year takes one week, the sophomore year two weeks, and the junior and senior years about three weeks apiece. Somewhat to my surprise, the plethora of topics listed can be effectively covered. To test this, we have given the same exams both to undergraduates and to students in the program. The students in the program easily outscored the undergraduates. This is a result of the students' quality, their maturity, and their dedication to making an effective transition.

TROUBLE WITH MATH AND THERMO

THE CHEMISTS HAVE the most trouble in two areas: mathematics and thermodynamics. Mathematics presents a big problem. While most students have studied differential equations, few can apply what they've learned to physical situations. Virginia's program teaches mathematics directly. Ours relies on graduate-level mathematics courses taken in the fall semester.

In contrast, the student's deficiency in thermodynamics is less expected and harder to rectify. While most of the students in the programs in Table II are graduates of ACS-accredited chemistry departments, and these departments do teach a required thermodynamics course, most of the students claim to have had little or no thermodynamics. I think the truth is probably more nearly what one student said, "Sure, I had all this stuff but no one ever acted like it was important."

We have tried to remedy this deficiency in thermodynamics by including material in the summer course. We have not yet been able to teach this material effectively, partly because an extremely abstract subject is being presented at a very rapid rate. After the summer, students do not feel that they understand thermodynamics. They are able to handle our graduate course in thermodynamics in the fall semester, but the experience is trying, demanding, and unpleasant. I know no simple way out of this problem.

The summer courses also contain no reference to engineering design. Our program, and several of the remedial ones, correct this by requiring that students with chemical backgrounds take a senior level design course. Our special students work much harder than our seniors, do better, and thus cause some resentment. I think pushing our seniors this way is healthy.

We've had two other problems with our special summer course which deserve mention. The first is that we have not been able to find an effective text. The reason is that ChE is almost completely taught in a sequential fashion. Everyone who studies sophomore thermodynamics intends to take the junior-level transport phenomena courses and the senior-level kinetics courses. This means that there is no single text providing an abbreviated overview of essentials of ChE in relatively simple terms. As a consequence, we have had to write a text, which we would be glad to make available to others with similar problems. We plan to revise and publish this text soon.

The second problem we have had concerns retaining minority students in the program. Both they and students who have been out of college three or more years find the mathematics required to be extremely difficult. As a result, we have preceded our special summer course with a one-week mathematics review, taught by people connected with our Affirmative Action Program. This has two results: it provides the minority and the returning student with the necessary mathematics and it also establishes firm friendships between these two groups. When the rest of the class convenes, the black students do not isolate themselves as frequently occurs in undergraduate classes.

. . . in a significant number of ChE departments, chemists make up the majority of North American graduate students.

I should emphasize that special summer courses are not substitutes for undergraduate training in ChE. It merely facilitates the student's ability to catch up throughout the regular academic year. Students whose backgrounds are in chemistry do less well relative to their classmates during the fall's courses. By spring, this difference disappears. In other words, the special summer course does not substitute for undergraduate training, but does allow students with different backgrounds to become competitive.

STUDENT RECRUITMENT

WHILE GRADUATE PROGRAMS which teach ChE to non-chemical engineers are multiplying rapidly, these programs often do not have large enrollment. In some cases, the faculty time spent planning them may exceed the student time in them. As a result, it is appropriate to ask where the students in this program will come from.

Most of the larger programs have found that the best source of students is the small liberal arts colleges located close to the university. These small colleges commonly do not offer undergraduate engineering programs. Moreover, because they are close by, the universities' reputations are exaggerated. The students recruited from these colleges have already rejected graduate training in chemistry. Considerable competition comes from schools offering a masters in business administration.

A second effective source has come from general mailings to chemistry departments, again largely at small colleges. We have been particularly successful with the minor campuses of major universities like those of New York and Ohio. We also receive good applications from high school teachers and from employees of local industries. Advertisements in ACS student newsletters and announcements in publications like *Chemical and Engineering News* and *Business Week* have not been effective.

One neglected aspect of these programs is their potential for social action. Specifically, they provide an opportunity to bring additional women and minority students into engineering. We have been very successful recruiting female teachers from local high schools. They are eagerly recruited by industry because their maturity and perspective makes them excellent candidates for middle management positions. We have been much less effective in recruiting blacks. Part of our trouble is that qualified blacks in chemistry choose medical school. Moreover, chemistry programs in predominantly black colleges sometimes have less stringent requirements in mathematics than those existing elsewhere. Nevertheless, we are convinced that we can effectively recruit minority students in the long term.

Once applications from qualified students come in, one must decide on how to admit them. Applicants commonly fall into two sharp categories. The first category are chemists with very weak undergraduate records. They are grasping at straws, desperate for any opportunity which promises a better chance of employment. The second category are students who are very good; they have decided to go on to graduate school and are carefully weighing options.

The best predictor of student performance is the quantitative aptitude part of the Graduate Record Examination (GRE). We require scores of at least 700 and preferably 750 to insure satisfactory performance. GRE aptitude scores are also useful in making a decision if the quantitative aptitude score is marginal. GRE advanced chemistry scores are less reliable, and reflect more the quality of the undergraduate institution than the quality of the student. Grade point seems the hardest to interpret. Basically, we have discovered that an entering chemist needs a (3.4/4.0) overall grade point to be effective. This is higher than that needed by entering ChE students.

If more than a third of my graduate class is not trained in ChE, the technical level of the material taught drops. Moreover, because the current trend in many departments is to reduce graduate course requirements, one may certify "engineering" graduates who know very little engineering.

WHAT DO GRADUATES REPRESENT?

NONE OF THE PROGRAMS outlined above can produce students who are identical with those trained completely in ChE. This can be especially true when large numbers of students are trained under the open admission strategy described above. This strategy is so wide and leads to such variation that generalizations seem meaningless. On the other hand, if sufficient remedial courses are required, the student should certainly become more and more similar to those trained completely in ChE.

The most intriguing question is, to what category do the students who graduate from programs built around rapid special courses belong? To answer this question, we contacted graduates of the special programs who are employed in industry. These graduates had more job offers at slightly higher salaries than conventionally trained masters engineers. Their reactions to the positions they accepted, and their supervisors' reactions to them are shown in Table III.

One conclusion is that those trained in chemistry have a more pragmatic attitude than those trained in engineering. For example, these students complain that the masters courses are too theoretical, while students with an engineering background feel the same courses are excessively applied. Apparently, those who move from chemistry into engineering make a mature and conscientious decision that their future lies in an industrial environment. They are very sensitive to industrial demands and respond accordingly. On the other hand, those trained in engineering go to graduate school in part because they are anxious to learn more of the intellectual basis of their discipline. This basis is more strongly represented in universities than in industry.

TABLE III.

Job Performance of Graduates

FROM THE GRADUATE

1. **How do you view yourself professionally?**
   A mixture of a chemical engineer and a chemist.
2. **To what professional organization(s) do you belong?**
   Most belong to both the American Institute of Chemical Engineers and the American Chemical Society.
3. **Does your job provide adequate professional challenge?**
   Yes—both chemical engineering and chemistry required.
4. **Did the program provide you with the professional training you expected?**
   Yes—worked effectively.
5. **In your job, do you see any professional advantages or disadvantages of your training compared with a traditionally trained chemist or chemical engineer?**
   Advantages over chemist; often translator between chemists and engineers.
6. **Do you have any other comments, suggestions or observations about the program?**
   Many courses were too theoretical; Masters thesis takes too long.

FROM THE SUPERVISOR

1. **How do you regard the professional training the graduate has?**
   Pleased so far.
2. **Do you see any advantages of this type of program over traditional majors?**
   A range of answers—from disadvantages to advantages to ignorance of program.
3. **How would you rate the graduates initiative, flexibility, maturity?**
   Much better than average on all points.
4. **Do these graduates require more supervision?**
   Most require an average amount of supervision. Those who require more do so because they are more productive.
5. **Do you have any other comments, suggestions or observations?**

Positive comments with good advice: e.g., "students should choose positions with a mixture of chemical engineering, chemistry;" "student quality more important than education;" "should use these people to replace chemistry Ph.D.'s."

A second conclusion which can be drawn from Table III concerns the students' effectiveness. This effectiveness is largely inherent in the students themselves. If they are bright, smart and aggressive before entering a program, they remain so afterward. As a result, their performance has more to do with their own character and ability than with any educational gloss. These students apparently perform a mixture of tasks. Certainly industrial jobs require a continuum of skills: they are not balkanized between science and engineering as are the university departments. However, industry recruits within the departmental structure and recruiters seek not specific individuals but people with specific types of certification. The students are being hired as engineers, but are working as hybrids.

AT YOUR UNIVERSITY.....

As THE ABOVE paragraphs show, there is now extensive experience on how to start a graduate program for teaching ChE to non-chemical engineers. If you decide to develop such a program at your university, you should do three things. First, decide on a strategy. If you plan to use open admissions, be sure you assemble sensible arguments defending the quality of your program. If you decide to require a significant number of remedial courses, think about how you plan to attract and retain smart students. If you decide to use special summer courses, you must discover a source of money to pay the additional cost.

The second thing you need to develop is a scheme for recruiting students. Any program which has an enrollment of less than about half a dozen will inevitably attract administrative criticism in hard times. You must decide whether to recruit locally or nationally. You should decide whether you are more attractive as ChE department or as a university. Moreover, the mailing list that you use to attract students should take advantage of undergraduate chemistry newsletters and local ACS meetings. Advertisements in *Chemical Engineering Education* won't help because chemists don't know this journal exists.

The third thing you should do is to talk to others with experience. Most, if not all, of the departments mentioned in this article are willing to send to any who are interested detailed material, including hour-by-hour course outlines, and copies of lecture notes. It would be foolish not to take advantage of the experience of others.

Finally, I wish you good luck. I find rigidly structured departments a real discouragement to free thought. I look forward to the time when it is easier for students to move back and forth between disciplines to develop unique skills which will make them professionally more interesting, interested and effective. □

EXPERIENCE AT ONE UNIVERSITY

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At THE HEART of our accelerated expansion program lies the premise that the holder of any baccalaureate degree has demonstrated intellectual maturity, and, with sufficient motivation, should be able to undertake almost any study of his choice. If such study were to be at the graduate level, he would have to have the background information to follow the advanced study, and, equally important, he would have to have enough "skill" in the discipline to compete at the graduate level with holders of the bachelor's degree in that major. With the foregoing in mind, we examined the course content of each departmental undergraduate course required for the B.S. Ch.E. to determine what topics a person entering our graduate courses would need as an absolute minimum. We also examined our undergraduate requirements in science and mathematics in the same light.

The chemical engineering component of our

TABLE 1. Ch.E. 5301 Analysis of Chemical Engineering Problems

Course Content

A. Stoichiometry[a]
   1. Units, dimensions, dimensional analysis
   2. Basic laws: Raoult, gas laws, corresponding states, Henry, Avogadro, non-ideal behavior
   3. System/surrounding concepts
   4. Driving forces/potentials
   5. Chemical equations/stoichiometry with generation and consumption rate expressions
   6. Composition/flowrate units, fluxes
   7. Accumulation/depletion expressions
   8. Multistream systems with recycle, bypass, purge
   9. Thermal variables: C_p, $\triangle H_R$, $\triangle H_M^o$, Q, w

B. Fluid Flow[b]
   1. General energy balance
   2. Pump work
   3. Prime movers
   4. Flow measurement
   5. Fluid-solid systems

Course Scheduling[c]

A. 1-4, 1 week; A. 5, 1 week; A. 6-8, 1 week; A. 9, 2 weeks; B. 1-3, 2 weeks; B. 4, 1/2 week; B. 5, 1/2 week

a. Text: Basic Principles and Calculations in Chemical Engineering, D. M. Himmelblau, 3rd Edition, Prentice-Hall.

b. Text: Unit Operations of Chemical Engineering, W. L. McCabe and J. C. Smith, 3rd Edition, McGraw-Hill.

c. Lectures 5 hours per week plus 2 to 4 hours problem-solving session.

accelerated program consists of twelve semester hours presented in four three-hour courses. The courses are designated as graduate courses, and are suitable for use as a graduate minor. The first six hours are offered in the fall semester in series. The first course covers material and energy balances and fluid flow. The second covers equilibrium- and rate-controlled processes, including separations techniques and heat transfer. The second six hours are offered as two parallel courses in the spring semester. One of them covers thermodynamics and kinetics, while the other includes design and practice oriented topics ordinarily thought of as "design". *viz.*, dynamic behavior, economic analysis, process simulation, and optimization techniques. Course outlines are presented in Tables 1 through 4.

The chemistry, physics, and mathematics components of our accelerated program do not vary significantly from those of the B.S. Ch.E. requirements. Engineering physics, organic and physical chemistry, and mathematics through differential equations are required, and can be taken in parallel with our accelerated ChE courses. Many students converting to chemical engineering have already had enough science and mathematics to meet our requirements, *e.g.*, the organic chemistry requirement is waived for those who have had biochemistry.

To compensate for the lack of ChE laboratory work in our accelerated courses, the students in this program are strongly urged (virtually required) to seek summer jobs in the chemical process industry. This three-month "practicum", combined with the previous year's work, embarks the students on our structured M.S. program with qualifications that we hope will enable them effectively to compete with B.S. Ch.E.'s.

The students' need for background information and skills to make them competitive with B.S. Ch.E.'s in graduate courses are kept uppermost in mind in teaching our accelerated courses. The first course (stoichiometry and fluid flow) is the first taste that most of the students have had of any type of engineering course. Considerable drill, both in study sessions and in home-

The chemical engineering component of our accelerated program consists of twelve semester hours presented in four three-hour courses. The courses are designated as graduate courses and are suitable for use as a minor.

TABLE 2. Ch.E. 5302 Analysis of Equlibrium and Rate Operations

Course Content

A. Equilibrium—Dependent Processes[a]
   1. Phase equilibrium
   2. Potentials versus equilibrium
   3. Ideal contactor concept
   4. Multicomponent, multistage contacting

B. Rate-Dependent Operations[b]
   1. Potentials and fluxes
   2. Transfer coefficients
   3. Analogies: heat, mass, momentum
   4. Mass applications
   5. Energy applications

Course Scheduling[c]

A. 1-2, 1 week; A. 3-4, 1.5 weeks; B. 1-3, 2 weeks; B. 4, 1 week; B.5, 1.5 weeks

a. Text: Stagewise Process Design, E. J. Hanley and H. K. Staffin, Wiley.

b. Text: Unit Operations in Chemical Engineering, W. L. McCabe and J. C. Smith, 3rd Edition, McGraw-Hill.

c. Lectures 5 hours per week plus 2 to 4 hours per week discussion/problem-solving session.

TABLE 3. Ch.E. 5303 Analysis of Physical and Chemical Behavior of Matter

Course Content

A. Thermodynamics[a]
   1. Philosophy and historical approach
   2. Applications: minimum, maximum, available work
   3. Chemical potential
   4. Criteria for phase equilibria
   5. Chemical equilibria

B. Chemical Reactions[b]
   1. Molecularity and rate expressions
   2. Order of reactions
   3. Mechanisms of reactions
   4. Effects of temperature and pressure on reaction rates
   5. Continuous stirred-tank reactor and tubular reactor
   6. Introduction to gradients and backmixing
   7. Engineering design

Course Scheduling[c]

A. 1, 2 weeks; A. 2-5, 4 weeks; B. 1, 1 week; B. 2-3, 2 weeks; B. 4, 1 week; B. 5-6, 4 weeks; B. 7, 1 week.

a. Text: Theory and Problems of Thermodynamics, M. M. Abbott and H. C. Van Ness, Schaum Outline Series, McGraw-Hill.

b. Text: Chemical Reactor Theory, K. G. Denbigh and J. C. R. Turner, 2nd Edition, Cambridge University Press.

c. Classes meet 3 hours per week plus 2 to 4 hours per week discussion/problem-solving session.

work assignments, is utilized. The students became at least familiar with, if not proficient at using, the various systems of units employed in engineering calculations, and become aware of the importance and significance of quantitative answers. Computational skills are reinforced in the second course (separations and heat transfer) but the amount of drill is reduced.

The two courses offered in the spring semester are taught on alternate days, the same as standard three-hour academic courses. Whereas the second of the fall-semester courses depended very heavily on the first, the two spring-semester courses are independent of each other. As it turned out, the students seem to benefit from the forty-eight hour stretch between classes which allows for mental induction of the information covered in the classes.

COURSE SCHEDULES

A TYPICAL SCHEDULE for a student with prior credit in organic chemistry or biochemistry for our accelerated expansion program is shown in Table 5. The first year is tailored for the requirements of each individual student. All, however, take both of the accelerated ChE courses each semester. At the conclusion of the first academic year of the program and their summer's experience in either industry or research, the students are ready to enter the master's program in our department. The core courses are shown in the second year of the typical schedule in Table 5. The second fall term consists of the same graduate courses in thermodynamics, heat transfer, and applied mathematics for chemical engineers as required of any master's candidate, regardless of background. We also anticipate that during the fall semester, each student will consult with all of our faculty with regard to research areas of mutual interest, and will select a major professor and a specific research topic. The student should complete any necessary literature search before initiation of the experiental portion of his program in late fall. During the spring term, the student will enroll in graduate-level mass transfer and fluid dynamics. He will also take a graduate technical elective on a subject chosen by his major advisor or graduate committee as being most beneficial to his research and career objectives. The experimental portion of his thesis will be undertaken no later than the start of the spring semester, and should be essentially complete by the end of the following summer. He will also be expected to take a graduate elective during the summer, leaving him free to write his thesis

TABLE 4. Ch.E. Analysis of Chemical Processes

Course Content

A. Economics[a]
   1. Time value of money
   2. Profitability criteria
   3. Amortization
   4. Capital and other costs

B. Optimization[a]
   1. Single-variable search
   2. Multi-variable search

C. Unsteady State[b]
   1. LaPlace transforms
   2. System dynamics
   3. Interacting systems
   4. Controllers
   5. Stability criteria

D. Simulation[b]
   1. Streams and modules
   2. Generalizations
   3. Network analysis

A. 4 weeks; B. 3 weeks; C. 5 weeks; D. 3 weeks.

a. Text: Class notes.

b. Text: Process Systems Analysis and Control, D. R. Coughanowr and L. B. Koppel, McGraw-Hill.

c. Classes meet 3 hours per week plus 2 to 4 hours per week discussion/problem-solving session.

TABLE 5. Typical Schedule

Fall I	Spring I	Summer I
Calculus I Physical Chemistry I Analysis of Ch.E. Problems Equilibrium and Rate Operations	Calculus II Differential Equations Physical and Chemical Behavior Analysis of Chemical Processes	Job in CPI or Research at TTU
Fall II	**Spring II**	**Summer II**
*Thermodynamics *Heat Transfer *Applied Math for Ch.E.'s Thesis Research	*Mass Transfer *Fluid Dynamics Technical Elective Thesis Research	Technical Elective Thesis Research
Fall III		
Technical Elective Write and Defend Thesis M.S. Ch.E. awarded		

*Core graduate course required for any M.S. Ch. E. candidate.

Although many of them may have had some calculus, chemistry and physics, their thought processes were definitely qualitative rather than quantitative, as is required in engineering education.

during the fall semester, simultaneously taking his final course.

Participation in our accelerated expansion program for the fall semesters of 1975 and 1976 is shown in Table 6, along with the backgrounds from which the students came. The physical chemists were in the accelerated courses for their graduate minor.

While the accelerated expansion program was developed with chemists and biologists in mind, we genuinely hoped that some students from non-technical fields would take advantage of it. The music major came to us in the summer of 1975 after completing the mathematics, physics, and chemistry courses usually needed for the B.S. Ch.E. degree. He was elated when we apprised him of the opportunity to earn the M.S. Ch.E. in about 28 months.

PROBLEMS AND PROGNOSTICATION

THE GREATEST DIFFICULTY was the non-quantitative background of most of the students. Although many of them may have had some calculus, chemistry, and physics, their thought processes were definitely qualitative rather than quantitative, as is required in engineering education. Special care had to be given in instructing these students in problem definition and interpretation of the answers.

The necessity of making assumptions was a difficult concept for many of these students. The assumptions could take the form of simplifications without which the problem was unsolvable, or of values of physical properties needed to complete the solution. In some cases, the students were exceedingly reluctant to assume an answer and then show that answer to be correct, or to use a difference between a calculated and an assumed value to predict a better assumed value, as is so often required in trial solutions.

Abundance of information in the form of data tables, graphs, equations, correlations, etc., as they appear in textbooks, handbooks, and the technical literature was a source of confusion. Use of information sources was an integral part of the course work.

Our experience with students from other fields pursuing graduate study in ChE has been most rewarding. Those who have completed the year of accelerated work are now holding their own in our regular graduate courses in thermodynamics, heat transfer, and applied mathematics. We shall continue to publicize our program both among potential students and potential employers. Nine students have accepted assistantships to start in the program this fall. □

TABLE 6. Enrollment in Career Expansion Program

Major	Fall 1975	Fall 1976	Fall 1977
General Chemistry	2	5	4
Organic Chemistry		2	1
Physical Chemistry	2	1	1
Polymer Chemistry		1	
Microbiology	1		
Music	1		
Physics			1
Pre-Medicine		1	2
Zoology	1		
Industrial Engineering		1	

A STUDENT POINT OF VIEW

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IN RECENT YEARS, many graduates with bachelor's degrees in the sciences and liberal arts have experienced difficulty in obtaining professional employment, and one means of arriving at a rewarding career is through advanced training in chemical engineering.

We are among the first group of students to participate in this innovative program, and have now completed our second year. The authors feel that, as a result of this program, we will be as well prepared to practice engineering as those students who receive both bachelor's and master's degrees in ChE.

LEVELLING PROGRAM

THE PREVIOUS ADVANCEMENT program required a minimum of three years of study, including two years of levelling plus the same 30 hours of graduate courses required of all M.S. candidates. Because of the long time span, this format did not appeal to many students who were interested in acquiring advanced technical skills. The present program is much more attractive, and is different only as the result of having condensed the two years of levelling work into one, without sacrificing the quality of instruction. The only disadvantage of the present structure is that the work is very intensive, and little time is available for relaxation and recreation.

Our professors realized that with such a fast learning rate, it would be easy for us to get hopelessly behind in our studies very quickly. To be sure that this situation did not develop, they were always available to answer questions. In addition, one afternoon per week was set aside as a time for us to ask questions and clarify the material, and this proved to be a valuable link in our learning process.

At the beginning of our studies, we needed to learn to think quantitatively and communicate in engineering terms. Consequently, we covered material slowly and in great detail, working many problems. As our competence improved, the problems became fewer in number but more complex. Almost before we realized it, we were thinking like engineers!

Because of the fact pace of our courses, there was no time for the usual laboratory work. There were also few opportunities to develop engineering judgment and common sense adequately, so vital elements were missing from our education. To rectify this situation, we were encouraged to obtain summer employment in industry following the year of levelling work. Those of us who who did work gained the practical experience that has made the remainder of our graduate courses much more meaningful.

THE PRESENT—AND FUTURE

COMPETING IN THE REGULAR graduate courses with students who, for the most part, have superior technical backgrounds has been a challenge. Several students have B.S. degrees in ChE plus several years of industrial experience. They invariably understand the problems better and fare better on tests. It is easy for those of us who have participated in the career advancement program to become discouraged when we cannot understand the concepts as readily as those with more experience. Our greatest satisfaction is the realization that we have learned so much about engineering in such a short time.

We are all engaged in research projects leading to the writing of theses, and have not found that we are at a disadvantage in this regard. However, one problem that has been common to all of us is finding enough time to devote to both our course work and research projects.

In interviewing for jobs, we have found that we are as acceptable to industry as students who earn both B.S. and M.S. degrees in ChE. Our opportunities for plant trips and our salary offers have been comparable to those of other graduate students.

Our educational experiences during the last two years have been somewhat unique as well as very exciting and challenging. It is our belief that we will be well prepared graduate engineers, and we look forward to the technical improvements we can make during our professional careeers as chemical engineers. □

GRADUATE ChE EDUCATION ON A STATEWIDE CLOSED-CIRCUIT TELEVISION NETWORK

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THROUGHOUT THE COUNTRY, colleges and universities are seeking to meet the educational needs of today's mobile society. The medium of television is being used most effectively to reach people who cannot conveniently attend classes on campus. The engineering community especially finds need for such educational opportunities because of today's rapidly changing technology. To provide the means by which practicing engineers can continue to keep abreast of current trends, the University of South Carolina (USC), in 1969, started *A* *P*rogram of *G*raduate *E*ngineering *E*ducation (APOGEE).

Most of the chemical and related industry in South Carolina is scattered throughout the state and is not located near the USC campus in Columbia. Thus, a majority of the practicing chemical engineers who desire an advanced degree in Chemical Engineering would not be able to attend regular on-campus classes. These engineers look to APOGEE as a means of continuing career growth. To meet this need, APOGEE offers graduate courses in ChE at remote locations throughout South Carolina via full-color video tapes and closed-circuit television broadcasts. The locations where APOGEE facilities are to be found are listed in Table I.

THE APOGEE PHILOSOPHY

THERE ARE SEVERAL ways in which a statewide television network could be used to offer courses for graduate credit. Professionally produced lectures, complete with rehearsals, video tape editing, and specially prepared notes would provide nearly perfect 'shows' for the student. In some instances, this technique has been tried with success. However, it is felt that student-teacher contact, where the student is free to ask questions during the lectures, is an important part of engineering education. Also, student performance has been found to be unaffected by imperfections in the lecture presentation. Thus, the additional time required for the making of professionally produced 'shows' is not time which is efficiently used by the instructor.

The philosophy with which APOGEE courses are prepared is one of keeping as much of the regular classroom 'flavor' as possible. Classes for the on-campus students are held in modified classroom-studios. The off-campus students attend classes in classrooms containing television monitors and video tape players. Course lectures are presented twice a week. One lecture is video taped before the on-campus students in Columbia. The video tapes are then distributed to the remote locations so that they may be viewed at the con-

TABLE I. Locations of APOGEE Facilities

Aiken, South Carolina
Barnwell, South Carolina
Camden, South Carolina
Charleston, South Carolina
Columbia, South Carolina
Duke Power; Charlotte, North Carolina
Dupont Savannah River Plant, South Carolina
Florence, South Carolina
Georgetown, South Carolina
Greenville, South Carolina
Greenwood, South Carolina
Hartsville, South Carolina
North Augusta, South Carolina
Oconee, South Carolina
Orangeburg, South Carolina
Rock Hill, South Carolina
Savannah, Georgia
Shaw Air Force Base, South Carolina
Sumter, South Carolina
Spartanburg, South Carolina
Waterboro, South Carolina

Thomas G. Stanford received the BSChE degree from Wayne State University in 1966, the MSE(ChE) degree and the MS(Math) degree from The University of Michigan in 1968, and the PhD degree in Chemical Engineering from The University of Michigan in 1977. He has worked for Monsanto Company and Continental Oil Company as a process chemical engineer. Since 1976, he has been Assistant Professor of Chemical Engineering at the University of South Carolina. His research interests are in the areas of chemical reactor engineering, mathematical modeling of chemical systems, and thermodynamics.

venience of the off-campus student. The other lecture is presented live on closed-circuit television both to the on-campus students and to the students at the remote locations. Because most of the off-campus students are not able to attend classes during regular business hours, this lecture is presented either on a weekday evening or on Saturday morning. It is in 'talk-back' format so that each student may talk freely with the instructor via telephone. Several 'Saturday in Columbia' class meetings are scheduled throughout the semester. All of the students come to Columbia for these sessions to take exams, to discuss homework, or to do experiments. Students are also free to contact the instructor by phone during regular office hours if they have specific questions.

APOGEE DEGREE PROGRAMS

APOGEE OFFERS MASTER of Engineering (ME) and Master of Science (MS) programs in ChE. Any person who holds a baccalaureate degree from an Engineers' Council for Professional Development (ECPD) accredited engineering school is eligible for admission to either of these programs. Prospective students who hold degrees from nonaccredited engineering schools will be required to take the Graduate Record Examination (GRE) prior to admission into a degree program. Under certain circumstances, persons holding degrees in related fields such as biology, chemistry, and pharmacy may be admitted into a degree program. Admission of such persons will be based on previous college studies, work experience, and any other factors deemed relevant.

The ME program requires a minimum of 30 semester hours of coursework for completion. The course requirements are listed in Table II. A student may elect to undertake a suitable engineering project in lieu of up to 6 semester hourse of FREE ELECTIVE credit. However, most persons who wish to obtain an ME degree choose to do coursework only. Because neither a research project and thesis nor an engineering project is required for this degree, it lends itself well to the APOGEE program.

The MS is a research degree. The student who receives this degree must successfully conduct research in a suitable area of ChE and document his work with a written thesis. The coursework requirements for the MS degree are identical to those listed in Table II for the ME degree. The student must elect 6 semester hours of thesis preparation (ENGR 799). These credit hours may be counted as part of the FREE ELECTIVE requirement for the degree. A student who chooses to do so may complete his coursework via APOGEE. Under special circumstances, the thesis research may be completed at a location other than the main USC campus in Columbia. This

TABLE II. Requirements for the ME Degree in Chemical Engineering

A. Required Courses	
Diffusional Operations	3
Chemical Engineering Thermodynamics	3
Chemical Process Analysis	3
B. Required Electives	3
One course to be chosen from the following	
Distillation	(3)
Chemical Reactor Design	(3)
Advanced Chemical Flow Systems II	(3)
A 700 level control course such as	
Dynamic Process Analysis	(3)
Computer Control I	(3)
Computer Control II	(3)
Modern Control Theory I	(3)
Modern Control Theory II	(3)
C. Free Electives	18
Graduate courses at the 500 level or above in engineering, mathematics, or chemistry. At least 6 of these credit hours must be in courses at the 700 level.	
Total Credit Hours	30

work would, of course, be conducted under the supervision of a member of the ChE faculty.

APOGEE also offers those who do not wish to pursue an advanced degree the opportunity to keep abreast of the latest technology. The College of Engineering at USC offers courses in energy systems, air and water pollution, computer process control, distillation, and chemical reactor design. In addition, the technical expertise of nationally and internationally known scientists and engineers is made available through video tape programs produced by the Association for Media-Based Continuing Education for Engineers (AMCEE) of which the College of Engineering at USC is a charter member.

THE SUCCESS OF APOGEE

THE APOGEE PROGRAM has experienced rapid growth since its inception in 1969. Table III shows the number of on-campus and APOGEE students in the graduate ChE program at USC for each year since 1971. This indicates that APOGEE has been well received by those chemical engineers in industry who wish to pursue an advanced degree in ChE.

TABLE III. On-Campus and APOGEE Students in the Graduate Chemical Engineering Program at USC

	ME		MS	
Year	On-Campus	APOGEE	On-Campus	APOGEE
1971	15	3	7	—
1972	14	12	8	2
1973	8	13	10	6
1974	4	23	11	4
1975	2	31	6	7
1976	1	31	6	4
1977*	0	25	8	4

*spring semester enrollment

The classroom performance of the off-campus students is also an indication of the success of the APOGEE program. It has been found that these students do as well as or better than the students who attend the classes live. The video tapes of lectures allow each student to go over certain parts of the material several times. This 'playback' feature has been a beneficial teaching tool both for off-campus and for on-campus students in the APOGEE program. The 'talk-back' broadcasts are well received by the students. These sessions often deal only with student questions. This student-teacher contact takes the place of that which is normally available to the on-campus student; contact which often teaches more than any formal lecture could. Thus, the APOGEE format of video taped lectures and live 'talk-back' television lectures has provided the student-teacher contact so important to engineering education and, at the same time, places no more demand on the instructor than preparation for a regular class would. APOGEE also provides direct interaction between the College of Engineering at USC and the industry of South Carolina. This interaction has not only stimulated discussions in the classroom but also provided a way of introducing practical graduate engineering problems into the coursework.

APOGEE has proven to be an unqualified success for both students and teachers. Its rapid growth and evolution make it a current and meaningful program of graduate engineering education. More information about the APOGEE programs in ChE at the University of South Carolina may be obtained by writing to the APOGEE Program Director, Dr. W. K. Humphries, at the College of Engineering, University of South Carolina, Columbia, South Carolina 29208. □

BOOK REVIEW: Uhl

Continued from page 149.

conventional for capital costs, operating costs and profitability criteria. The emphasis in capital cost estimation is for "order of magnitude" and factored estimates. The profitability methods include discounted cash flow. Where this book differs from other works is in the presentation; it is terse and striking. There are many tables and figures to elucidate the concepts and examples to illustrate them. Some new, useful compendia appear; these are the fruit of the prodigious labors of Professor Woods. There is a survey of the single (Lang) factor approach to compute capital cost from the sum of the cost of the major pieces of equipment. Also, there is an extensive critical view of the various schemes for using more detailed factors in capital cost estimates. Unfortunately only passing mention is given to continuous interest, uncertainity analysis (which is not mentioned as such), and sensitivity.

In several places the progression from simple, quick and rough to detailed time-consuming and close estimates is dramatized. The laudable purpose here is to inspire students to develop judgement.

Also a note about the teaching of engineering economics is in order. In his preface, Woods notes: "many students undergo a long induction period before they appreciate some of the concepts". My experience confirms this view, but I would add that practicing engineers grasp the concepts readily, no doubt because they are familiar with business background and practice.

The initial chapter, The Decision Makers, is a vigorous view of the engineer in society, his responsibilities, and ethics in practice. Although the tone is idealistic, and perhaps naive, it is praiseworthy. A quote from the book is to the point "... engineers are, by and large, the decision makers in industry and technology . . ." (Actually we should be more influential than we are, but by nature we are less assertive than others, e.g., company managers).

The second chapter presents the economic environment. Basic economic concepts are covered: supply, demand, competition, cash flow, allocation of financial resources. Unfortunately, because of its brevity the treatment serves only to stress the need for such an overall perception.

The couching of the economic evaluation in terms of accounting practice is commendable. For cost data and for project authorization, we must deal with accounting and financial types, so engineers must speak the "accounting" language.

Outstanding merits of the work are the introduction of pertinent material from other fields, some novel approaches, homilies and examples designed to evoke engineering judgment, useful compendia of cost data, good specimen forms for the preparation of cost estimates, provocative problems, a valuable bibliography and an excellent glossary of relevant terms.

The book is compact, perhaps excessively so for the wealth of ideas, examples, tables, etc., which it contains. It has only 340 pages. For much of the material an extended, amplified treatment would be preferred, particularly in its service as a textbook. Its classroom use may require expansion on some topics in lecture by the instructor to derive the maximum benefit. This unique, diverse, rich, exciting book should also provide an excellent review or an introduction to this subject for practicing engineers. □

RETZLOFF: Reaction Engineering

Continued from page 168.

the multiplet theory of Balandin [3] and the premise that the catalytic activity is determined by the compatability of the catalyst surface geometry for the reaction being considered. The key ingredients are the lattice parameters and the arrangement of catalyst surface atoms which are correlated with catalytic activity. The electron band theory of catalysis [4] is principally applied to transition metal and alloys and seeks to relate catalysis, principally through the chemisorption step, to the electronic properties of the bulk solid. The subject of the electron theory of semiconductor catalysts represents a review of the work of F. F. Vol [1] Kenshtein [5] on the role of the Fermi level in acceptor and donor reactions occurring on a semiconductor catalyst surface. The final topic, the charge transfer theory of catalysis, starts with a review of the work of Hanffe [6] and Lee [7, 8] on change transfer reactions. The effects of D.C., symmetric A.C., and antisymmetric A.C. capacitively applied electromagnetic fields on the charge transfer catalytic reaction rate are discussed. The results of acoustically coupled phonon excitations on these same reaction rates are developed. Within this general context the effects of surface states (as distinct from the bulk energy states) on the catalytic processes that occur on transition metal oxides is considered [9, 10]. □

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SHINNAR: Interface Between Industry and the Academic World

Continued from page 153.

just said. Kurihara also analyzes the information flow in the unit and diagnoses the main difficulty of control. The main parameter controlling the performance is the level of coke on the catalyst particle. This again depends both on the reactor performances as well as on the regenerator condition. The time scale of the coke build-up is large, on the order of an hour, whereas the residence time of both oil and air flow in the unit is measured in seconds. This long time lag leads to difficult control.

What the scheme in Figure 2 really does is minimize this interaction by keeping the regenerator conditions more constant. To do this we need an additional measured variable on the regenerator to be kept constant.

But if one looks at the control scheme in Figure 2 from the viewpoint of an operator, an immediate deficiency is apparent. The reactor, which is the main part, has no control, and the operator has no direct way to change the level of conversion in the unit. Lee and Weekman [3] discuss this in detail and show that this can be corrected by a cascaded feedback loop, given in Figure 3.

The control scheme in Figure 3 is much smoother and faster than the controller in Figure 1, which is a significant improvement. It has, however, some of the same deficiencies, namely, that it does not have sufficient manipulated variables to allow the operator to really achieve what he needs to do, which is to be able to adjust the steady state of the unit to meet varying process requirements and varying constants. In the refinery we don't make money by reducing the level of the control input needed. This is fixed when we choose the manipulated variable. We make money by being able to work close to a constraint, and both our goal and the nature of the constraint change with time.

In reality the operator does this or tries to do this by using additional manipulated variables, which don't appear in any scheme. He changes the feed allocation between different units. Furthermore, he can change catalyst activity by adding and withdrawing more or less catalyst or ordering a different catalyst.

The fact that Kurihara's work did not lead to a useful controller design does not detract from the usefulness of his work. In fact, the complexity

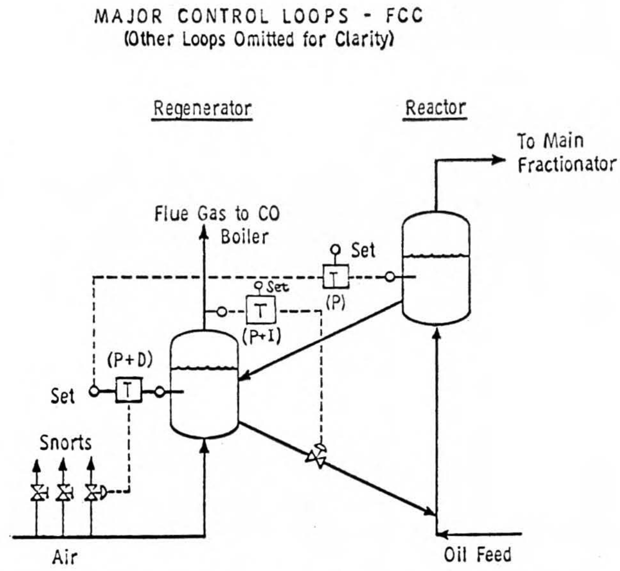

FIGURE 3. Schematic of modified control scheme.

of the problem is such that one cannot expect *academia* to do that, unless there is a real integration with an industrial project. But that is not necessarily what we want from *academia* here. It is sufficient that we understand in what way the modern control theory used in the example could be helpful in designing industrial controllers. And the negative results of Kurihara's work are far more illuminating and important than the positive ones.

OPTIMAL CONTROL

I LEARNED FROM THIS example some of the basic shortcomings of optimal control as well as some of its advantages. For example, it makes clear that the standard formulation of costs and profits in optimal control, both deterministic and stochastic, have very little to do with real costs and profits and are only indirectly relatable. Furthermore, complex chemical systems are often not controllable in the full sense, and controllability in the mathematical sense is not the same as in the operational sense. I realized that those decisions which are made before one writes the algorithm, namely, which variables can be measured and which should be manipulated, are more important than the choice of the algorithm itself or the profit function. The main result of the algorithm is in determining the dominant roots and in decoupling the reactor and the regenerator. This is rather insensitive to the profit function used.

We could have obtained some of the same results using the methods proposed by Rosenbrock [4] for multivariable controller design. This illuminates one of the main paradoxes of optimal control in process control application.

On the one hand it is clear that the term *optimum* is highly misleading. It is not a real optimum in any sense and can give rather unusable controllers, as pointed out by Rosenbrock [4] and myself [1]. It is also in no way a straightforward design algorithm but depends on the skill and understanding of the designer much more than the Ziegler-Nichols method does.

On the other hand optimal control can provide very useful information to the designer. But this information must be integrated into a design procedure which checks the stability and sensitivity of the total system and its overall performance. The test of the algorithm is outside its formulation and needs a good understanding of the system.

The properties of the algorithm are often less important than the quality of the clues it can provide and the way it integrates with the designer's knowledge, experience, and intuition.

But modern control literature is not written this way. The unsuspecting reader gets the impression that he really deals with a straightforward design algorithm. Even as great an expert as Rosenbrock attacks optimal control on philosophical grounds; that is, he heads in a direction that minimizes the intellectual contribution of the engineer. On the other hand we heard a repeated claim at this conference that successful use of optimal control requires too much of a theoretical knowledge.

Personally I don't worry about algorithms or computers eliminating the engineer. Complex design algorithms need a much higher degree of intellectual input than present methods and increase the need for highly trained personnel. I feel Rosenbrock attacks an image that modern control literature projects more than a reality. The real problem is that in the present state modern control theory is not easily integrated with the way an experienced engineer designs a control system. We have mathematically become so complex that even professors have stopped understanding each other. What we need is to translate the results of modern control theory into the language of the practicing engineer and to present the insights obtainable in a simple form. When results and insight are presented in a simple form, they often look obvious, but this does not detract from their value. It simplifies them.

For many purposes this is definitely possible. The work that Prof. MacFarlane talked about at Pacific Grove, California is a prime example of what can be done to translate the work done in one method to other mathematical languages familiar to the engineer. Morton Denn showed that a PID controller can be obtained from an optimal formulation. Our own work at present deals with this problem, and I'll mention here just two items.

Consider, for example, the case of a simple single-loop controller for an overdamped system, with no inverse response. In most cases it is sufficient to model this by a first order or second order system with a delay in series.

$$G_p(s) = \frac{e^{-\theta s}}{1 + \tau s} \tag{1}$$

or

$$G_p(s) = \frac{e^{-\theta s}}{1 + 2\tau s + \tau^2 s^2} \tag{2}$$

If we design an unconstrained deterministic optimum controller for Eq. (1) we will get a controller of the form

$$G_c(s) = \frac{e^{-\theta}(1 + \tau s)}{1 - e^{-\theta(1+s)}} \tag{3}$$

which is really a proportional controller with a dead time compensator very similar to the Smith dead time compensator. The system is in practice unstable as a small change in $G_p(s)$ will lead to instability. We can make it stable by constraining the control effort, but any experienced engineer will reject the controller because his experience tells him he does not want a proportional controller with a small gain and a dead time compensator.

Somehow we have to make an attempt to bring engineering back to our research. Nowhere is this more felt than in theoretical engineering and especially in control.

Using Eq. 2 for the model will add derivative control action. There are several ways in which we can force the algorithm to give us integral action. One given by O'Connor and Denn [6] uses constraint on the derivative of the control.

Denn also showed that by using a Pade approximation for the delay we will get a simple PID controller and that a suitable constraint will even lead to controller settings very similar to that obtained using the Ziegler-Nichols method.

Unless we use very complex stochastic formulation for the structure of the inputs, optimal algorithms will always end up in controllers similar and equivalent to those already is use, a combination of P, I, and D control with a dead time compensator and a smoothing filter. In that sense optimal control has neither led to any surprises nor to a design algorithm. In all cases we have to evaluate the results in terms of stability, sensitivity, and overall performance, and adding more criteria is only doing the same thing in an inverse way.

This does not mean the results are not very interesting. The fact that we know our empirical controller is very close to some clearly defined unconstrained optimum is very useful. Furthermore, we can get clues on proper design and tuning of dead time compensators.

On the other hand optimal control made some very significant contributions to the design of sample data controllers for the same case. I am referring here to the work of Box and Jenkins on control strategies suitable for human operators.

Take for example the above case. A simple suitable discrete model for the same process could be

$$G_p(B) = \frac{W_0 - W_1 B}{1 - \delta B} B^{k+1} \tag{4}$$

In their notation the output of the process Y_t can be written

$$Y_t = G_p(B) u_t + N_t$$

where N_t is the disturbance (or noise).

Box and Jenkins have an elaborate procedure to identify the input using nonstationary models for the noise. For most cases they recommend a noise of the form

$$N_t = \frac{1 - \lambda B}{1 - B} \alpha_t \tag{5}$$

Actually as McGregor [9] has shown this system is equivalent in the state space description to the following system

$$\begin{bmatrix} X_{1,t+1} \\ X_{2,t+1} \end{bmatrix} = \begin{bmatrix} 1+\delta & 1 \\ \delta & 0 \end{bmatrix} \begin{bmatrix} X_{1,t} \\ X_{2,t} \end{bmatrix} + \begin{bmatrix} W_0 \\ W_1 \end{bmatrix} \Delta u_{t-k-1} + \begin{bmatrix} 1-\lambda \\ \delta(1+\lambda) \end{bmatrix} \alpha_t \tag{6}$$

$$Y_t = [1\ 0] \begin{bmatrix} X_{1,t} \\ X_{2,t} \end{bmatrix} + \alpha_t$$

For an example, we will choose $\tau = 1$ and $\theta = 0.5$, and the sampling time T equal to 0.25. An unconstrained optimization will give us the following results ($\lambda = .5$)

$$u_t = -.5\,(\Delta u_{t-1} + \Delta u_{t-2}) + 2.26\,(\epsilon_t - 0.78\epsilon_{t-1}) \tag{7}$$

where u_t is the control action. Δu_t is the adjustment in control action and ϵ is the diviation of the measurement from the desired value.

This is a simple controller which uses just two measurements and two previous control actions. However, it can be rewritten in a different form.

$$u_t = -(1-\lambda)(u_{t-1} + u_{t-2}) + \frac{1-\lambda}{W_0}\left[\epsilon_t + (1-\delta)\sum_{i=1}^{t} \epsilon_{t-i}\right]$$

which shows that this is really a PI controller with a simple dead time compensator. The real value of this work is that, with a very simple strategy which an operator can easily handle, we can approximate a sophisticated controller. Furthermore, by adjusting the coefficients of these four numbers we can even include a filter or a lead compensator. The approximation is very good and even has some advantages as it avoids, for example, integral saturation.

But it is not straightforward. We note that the gain, as well as the coefficient of the compensator, depends on λ. Theoretically, the noise parameter λ can vary between −1 and +1. But only values between 0.5 and 1.0 will give controllers with acceptable stability margins for the gain. For others we will again have to constrain the control action to achieve stability, and if we look at the constrained controllers they are not sufficiently different from each other to justify any strong efforts to differentiate between them.

Evaluating the designs for different λ and even for more complex structures of noise gives very interesting and illuminating results, but the final design must take into account the proper stability margin, which is not part of the algorithm. In many cases stability will be the overriding final constraint; in others the structure of the noise might be more important. As this is not a lecture on controller design, I will refer you to our original paper [7].

It is true that in some sense the results of Box and Jenkins can be obtained both from classical theory or from the state space formulation. But this is hindsight. It is hard to guess that a noise structure such as in Eq. 6 is really one of the few that gives a good industrial controller. Nor did anyone else come up with such simple effective controllers for operators. But once we have them there is an advantage to translate them to a more familiar language.

This as an example of a really unforeseen result of optimal control that can be translated to the language most control engineers are familiar with. People with a background in quality control will prefer the original formulation. People with a long experience in classical process control will prefer to talk about dead time compensators, PI controllers, phase lag and phase lead compensators, and filters.

SUMMARY

THERE ARE PROBABLY many really valuable results hidden in the literature of modern control that merit being brought to a form useful for the control engineer. But we need to extract them, test them, and bring them to a form where they are useful tools in real empirical design.

The academic world is probably the only one that could do it and publish it, but we need not only people who are ready to do it but also some change in emphasis and value judgment in the academic community, especially in the U.S.

A thesis like Kurihara's is not exactly the prime example of what we value. It contains no rigor, no experiments, and no new theory. If he had spent five years and built a small FCC unit and put a trivial controller around it, at least part of our academic community would have admired it. It would have been rather useless, since it is very hard to build a small FCC with the same dynamic behavior. In real design we would use simulation anyway, and rigor would not help us since this is not our problem. What would have helped us if we would have pointed out what was wrong with his results. Very few students would today dare to do it.

This is sad. The value of theoretical work in industry as well as in scientific work is much greater in the failure mode than in the positive case. If a good sensible theory fits the data or vice versa, we learn rather little, especially if the theory is known. An experienced theoretician can guess the form of the result even without solving it. But when a reasonable theory leads to strong contradiction with experiments or our experience we learn something.

I learned this the hard way. When I started, one of my first students studied non-Newtonian liquid-into-liquid jets. We solved the equations for the power law fluid and were quite proud and tried to confirm them. Our first experiments showed some very strange effects, totally in contradiction of what theory predicts. We dutifully recorded them and finally found a set of narrow conditions where the experiments agree with theory. If I had had the sense to concentrate on the strange effects, I would have had a first rate pioneering paper instead of a rather standard one. But I learned my lesson. When we studied atomization of non-Newtonian fluids, we had a very solid linearized stability analysis for any fluid and were able to show that there are fluids for which the linearized theory does not apply.

We therefore have to create an interface between the industrial practitioner and the rigorous researcher, and the only way I can see it is to start working on the fundamentals of our profession—trying to obtain an understanding of the design process itself, which never really is algorithmic but rather interactive and intuitive and strongly relying on informed judgment.

We have boxed ourselves in so much with preconceived notions about how a good paper or thesis should look that real engineering research becomes rather hard. This is strange. Even the hard sciences or mathematics feels less constrained as to what a paper should look like than we do. And there is no part of engineering where people are as ferociously prejudiced and constrained as in the academic control field in the United States.

I admit the problem is not easy. A thesis like Kurihara's or Kestenbaum's [5] is much harder to judge and evaluate. The same applies to any work dealing with dirty problems and with ill-defined notions such as design. Furthermore, when complex results are translated into simple language, they often sound obvious and, to those without experience, sometimes trivial. But we are engineers with all the advantages and disadvantages, and fleeing into sterile mathematics does not solve anything. The relevance of such work is just as hard to judge. Nor does such work necessarily make the best preparation for a student's career.

We therefore have to create a climate in which such work can flourish. We also need to create a basis of financial support for it. Research on servomechanisms is supported by NASA and DOT, but real process control, just as most research on process design, has no home either at NSF or any other agency and very meager industrial support. This is again purely a question of the intellectual climate. The needs and potential for significant improvements in process control are at least as big as those in many areas which have ample support.

Let me make one thing clear. I do not want to imply that what I outlined is the only research or even the main research control engineers should do. In process control we suffer already far too much from preconceived notions of what the only present thing to do is, and I do not want to add to this. Sound rigorous theoretical work and well-conceived experimentation can make significant contributions to modern control. But the nature of the problem is such that, unless we obtain a better understanding of the design process itself, many of the most valuable units of our work will remain useless, and some of our theoretical work will go into directions where no real need exists. We therefore have to create an interface between the industrial practitioner and the rigorous researcher, and the only way I can see it is to start working on the fundamentals of our profession—trying to obtain an understanding of the design process itself, which never really is algorithmic but rather interactive and intuitive and strongly relying on informed judgment. It will be a difficult but interesting and gratifying task.

Let me finish with another story relevant to the present state of research in the engineering profession. I read once a strategic analysis of the Maccabean War, an important event of Jewish history. The analyst showed that Judah, the Maccabean, was a military genius, the inventor of guerilla warfare, the first to be able to handle the Greek phalanx. But having beaten the Greeks in a historic battle, he forgot his lesson. He really dreamed of becoming a Greek general leading his army in a phalanx. Doing that he was sadly beaten. His brothers followed his first lessons, which led to final victory. I do not want to elaborate on this example. □

NOTATION

α_t = white noise variable
B = backward shift operator
$G_p(B)$ = plant discrete transfer function
$G_p(s)$ = plant continuous transfer function
k = defined by $\theta = k \cdot T + c \cdot T$ (k is an integer)
δ = defined by $e^{-T}{}_t$
λ = noise parameter
X_t = state vector
Y_t = output
τ = filter time constant [Eq. (1)]
θ = time delay [Eq. (1)]
ϵ_t = deviation of output from setpoint
u_t = control action at time t
T = sampling period
$W_0 = 1 - \delta^{1-\lambda c}$
$W_1 = \delta - \delta^{1-\lambda c}$
$c = \theta/T - k$

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ChE books received

TWENTY LECTURES ON THERMODYNAMICS

By H. A. Buchdahl, Pergamon Press, 1975

These twenty lectures present a coherent, bird's eye view of phenomenological and statistical thermodynamics. According to the author they are largely elementary in character, pedagogic in purpose and proceed in a way, which here and there, "allows physical intuition to take precedence over mathematical niceties". Nevertheless the text is abstract and mathematical. Some readers may prefer other approaches. □

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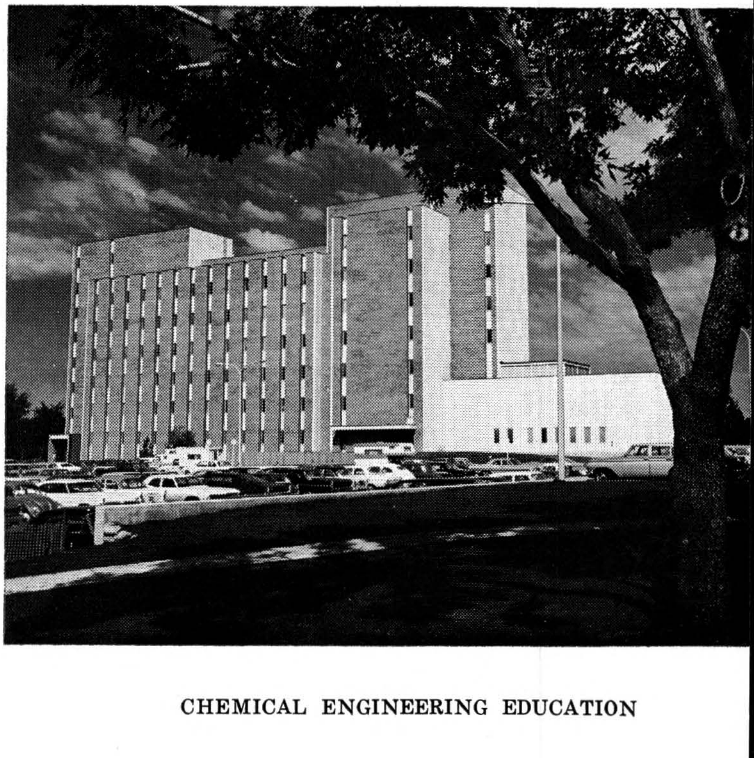

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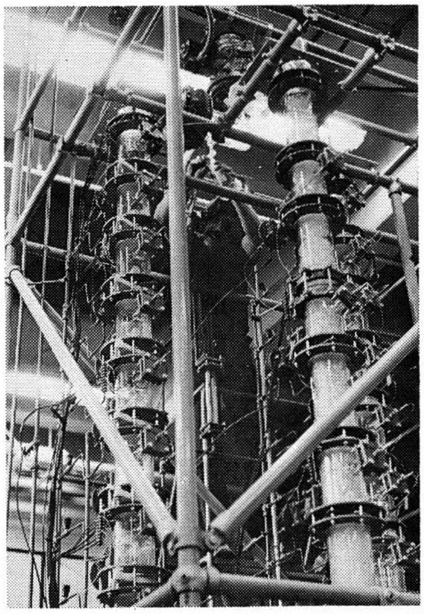

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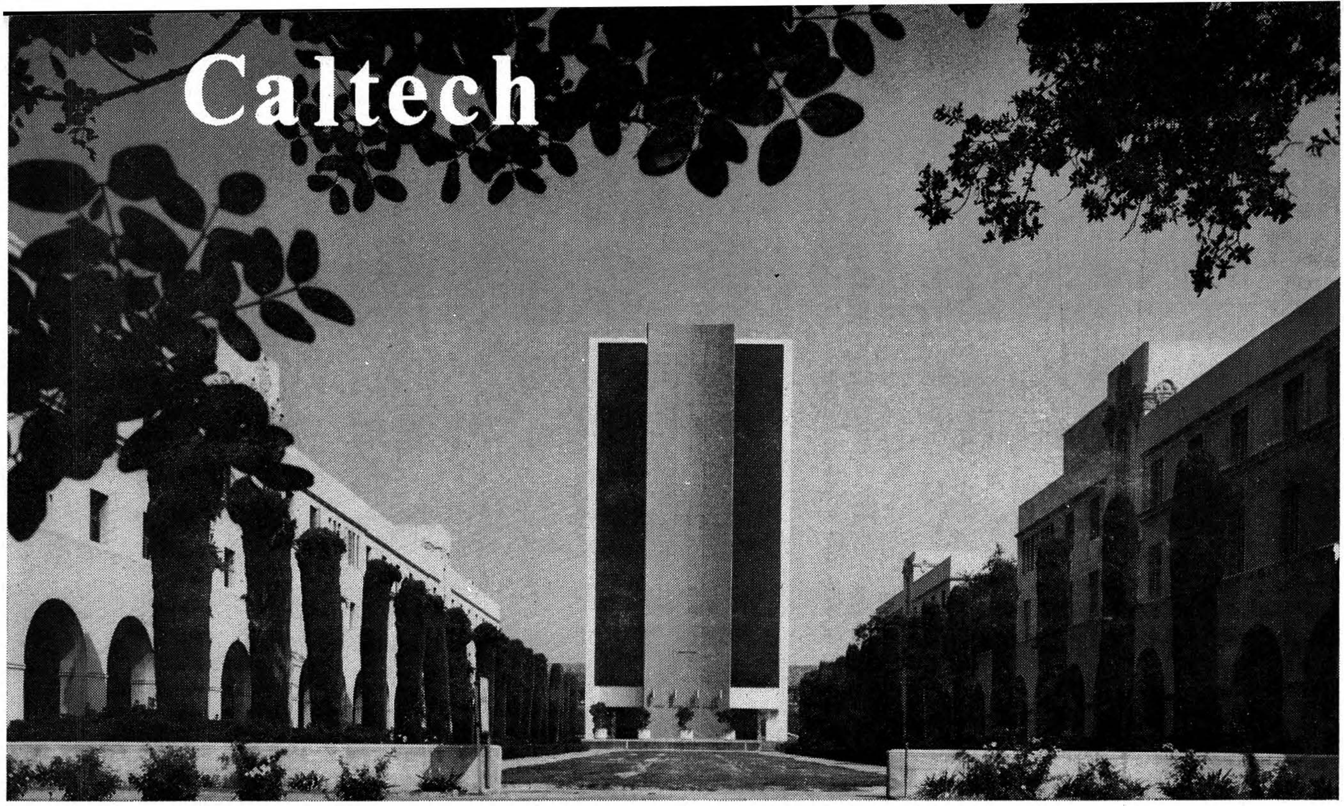

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NICHOLAS W. TSCHOEGL, Professor
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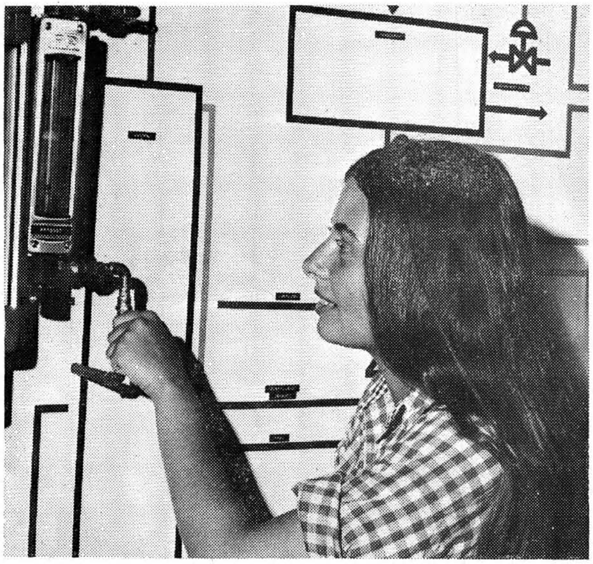

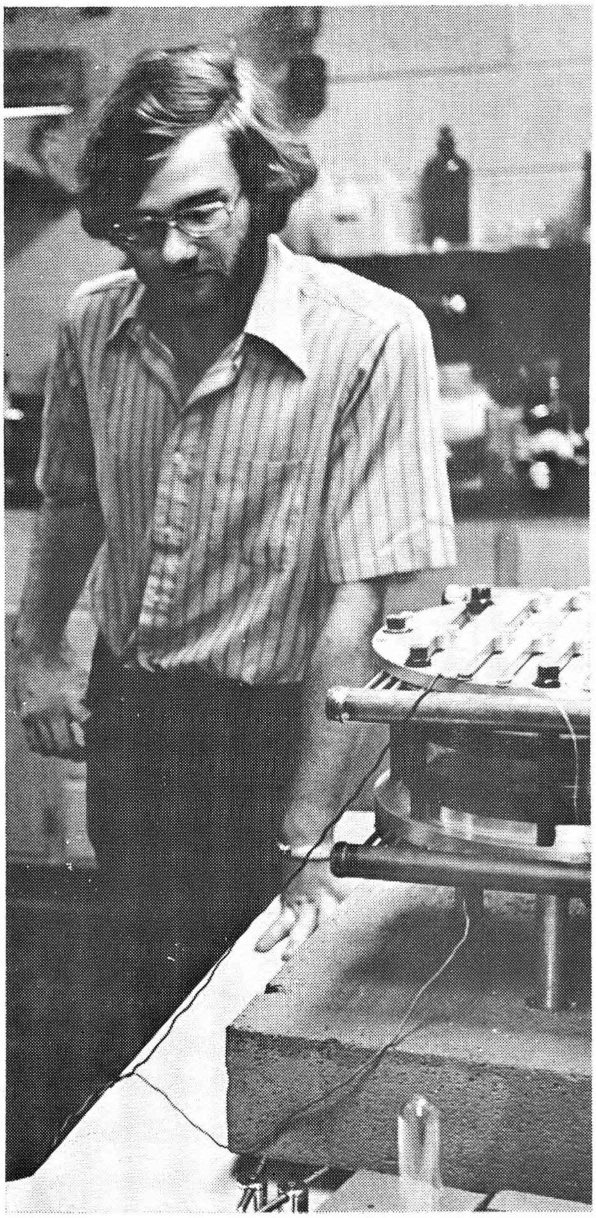

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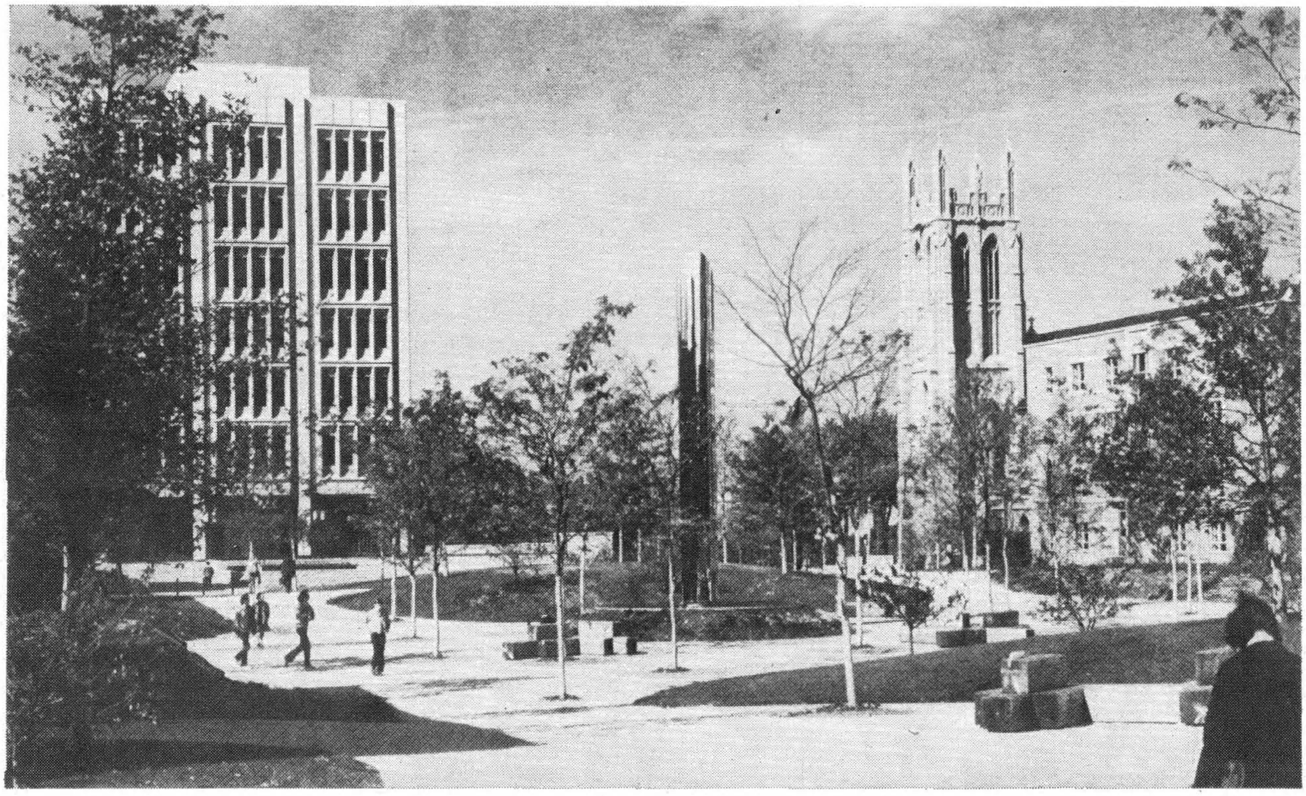

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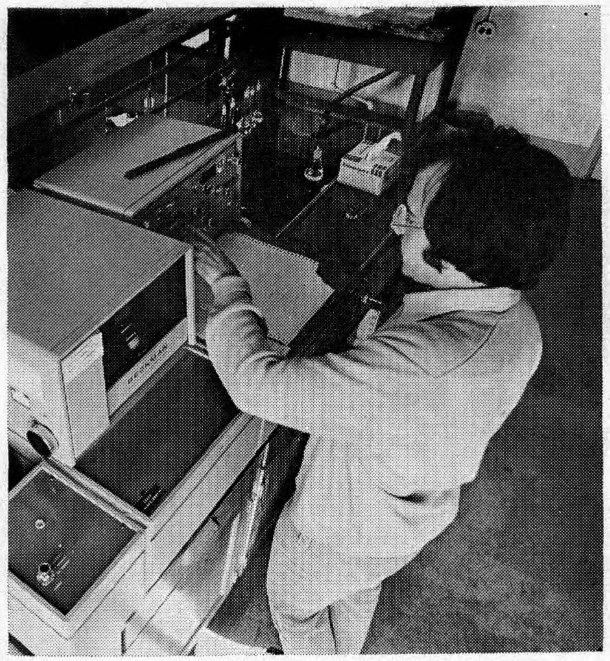

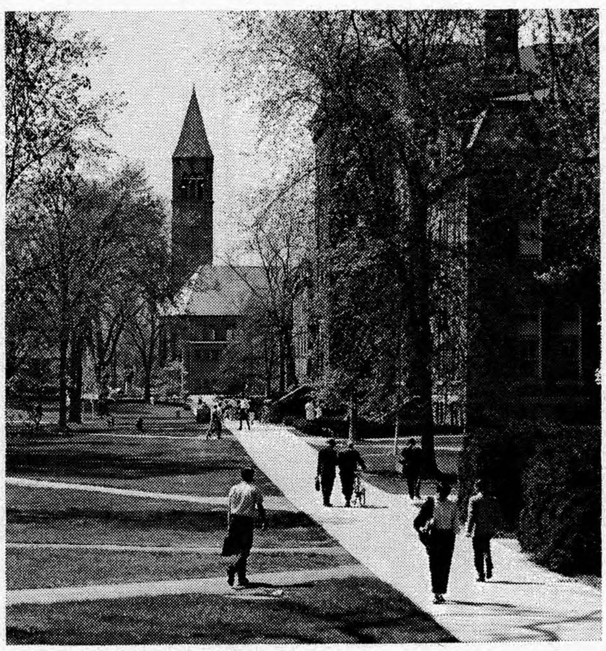

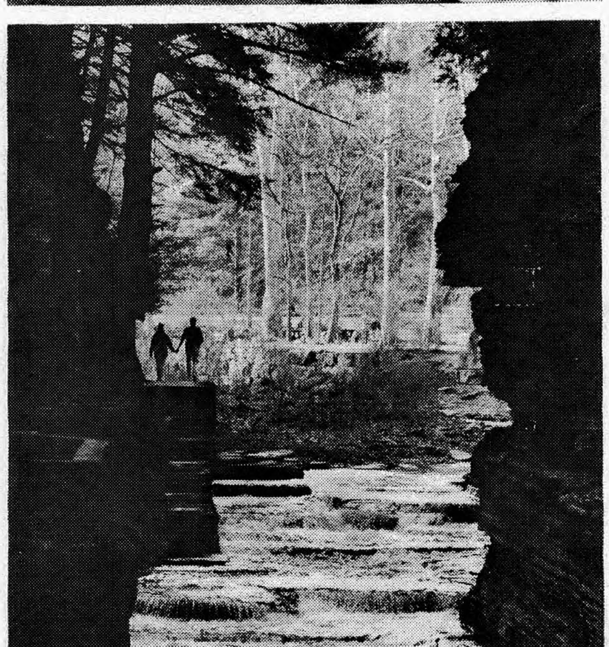

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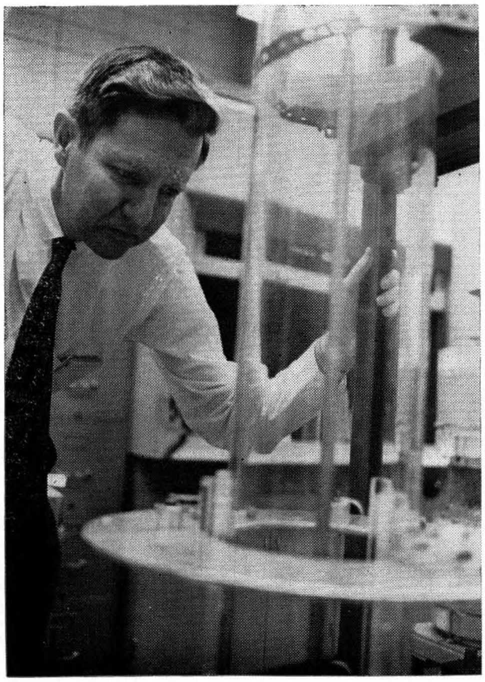

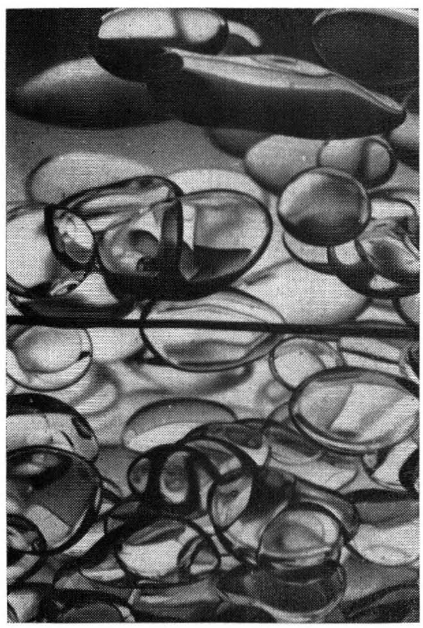

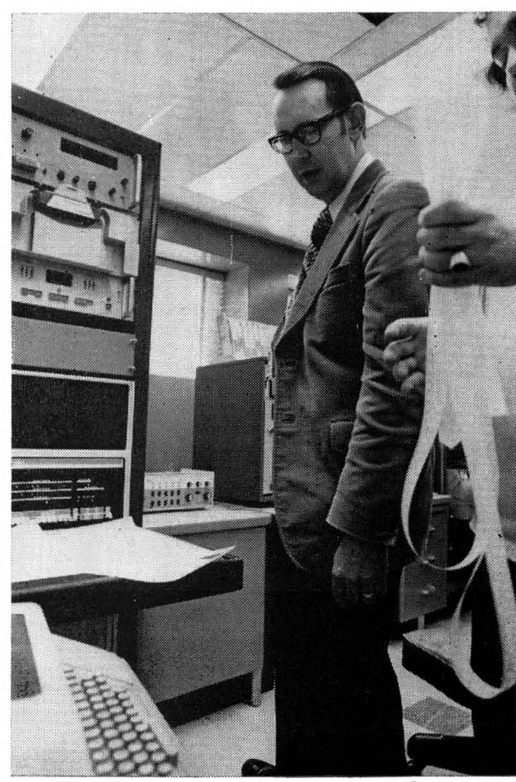

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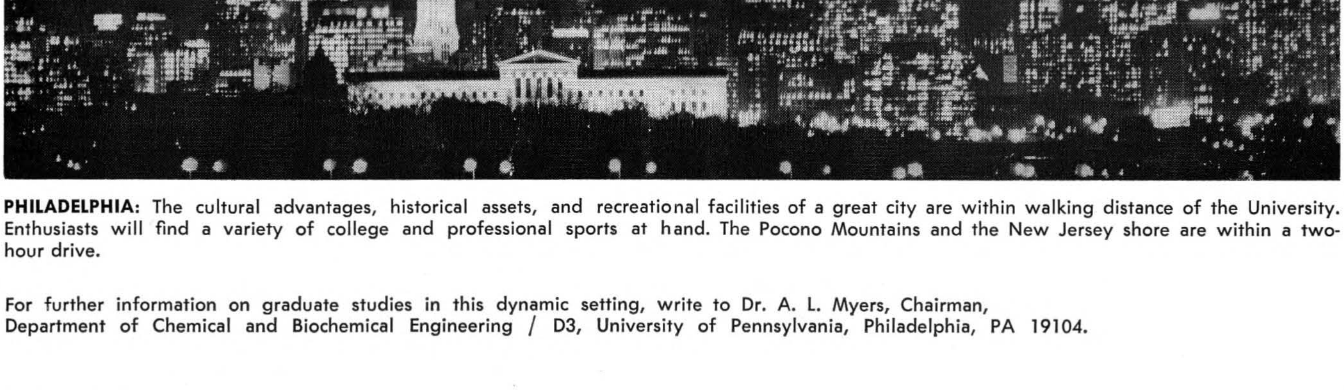
Transport Phenomena

The faculty includes two members of the National Academy of Engineering and three recipients of the highest honors awarded by the American Institute of Chemical Engineers. Staff members are active in teaching, research, and professional work. Located near one of the largest concentrations of chemical industry in the United States, the University of Pennsylvania maintains the scholarly standards of the Ivy League and numbers among its assets a superlative Medical Center and the Wharton School of Business.



PHILADELPHIA: The cultural advantages, historical assets, and recreational facilities of a great city are within walking distance of the University. Enthusiasts will find a variety of college and professional sports at hand. The Pocono Mountains and the New Jersey shore are within a two-hour drive.

For further information on graduate studies in this dynamic setting, write to Dr. A. L. Myers, Chairman, Department of Chemical and Biochemical Engineering / D3, University of Pennsylvania, Philadelphia, PA 19104.

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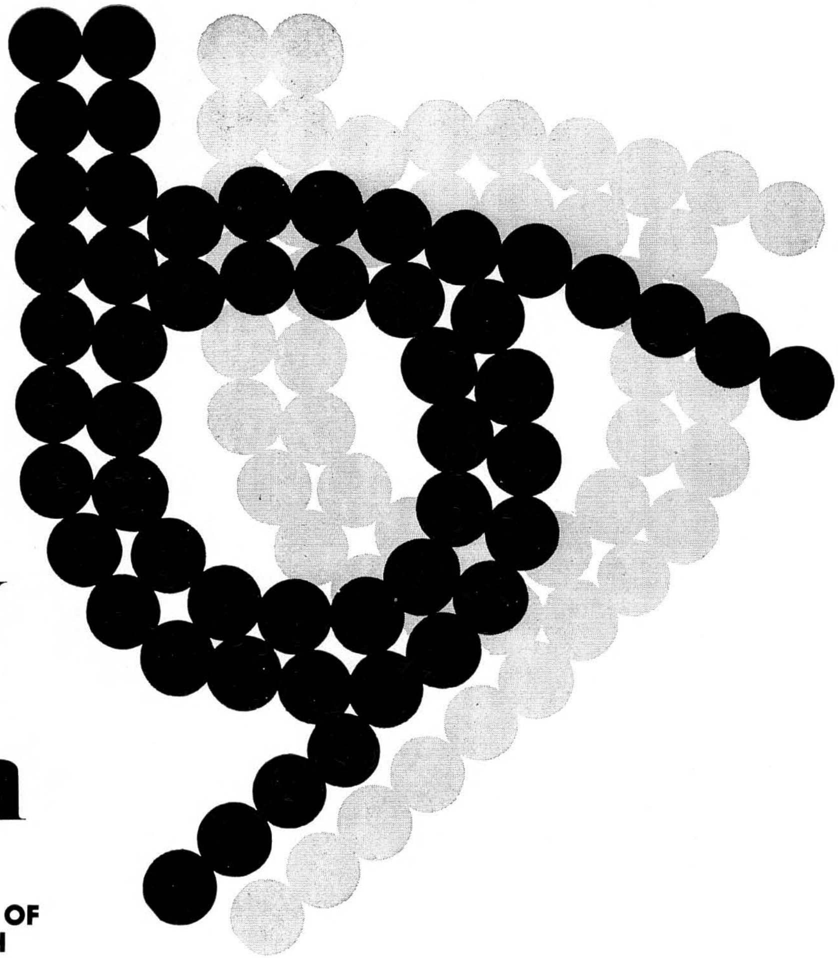

University of Pittsburgh

Sixty graduate students, along with 300 undergraduates, pursue their education on three floors of Benedum Hall. The facilities are modern and excellently equipped. Graduate applicants should write:

Graduate Coordinator
Chemical and Petroleum Engineering Department
School of Engineering
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UNIVERSITY OF PITTSBURGH

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PROGRAMS AND SUPPORT

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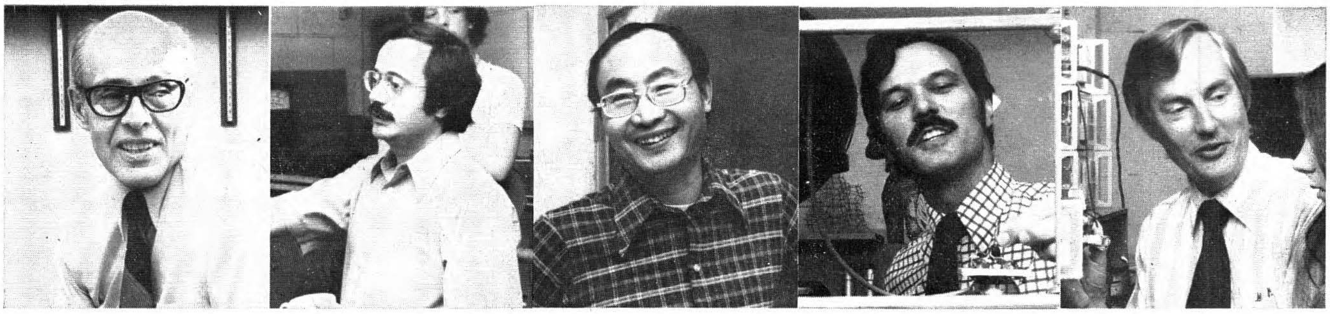
PITTSBURGH

The city leads a rich cultural life in an exciting geographic and social setting. Pittsburgh Symphony Orchestra, under the direction of Andre Previn, ranks high. A wide range of musical events rocks Heinz Hall. Pittsburgh Laboratory Theatre and Pittsburgh Public Theatre take innovative approaches to drama. Natural history displays at Carnegie Museum and art exhibits at the new Sarah Scaife Gallery draw over a million visitors yearly. For sports followers, Pittsburgh offers Pirates, Steelers, Penguins. And skiers find a variety of slopes just a half-hour, uphill drive from the city.



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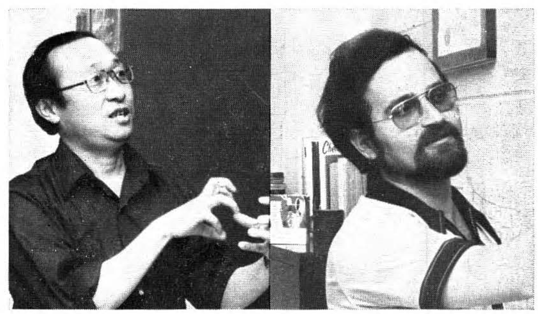

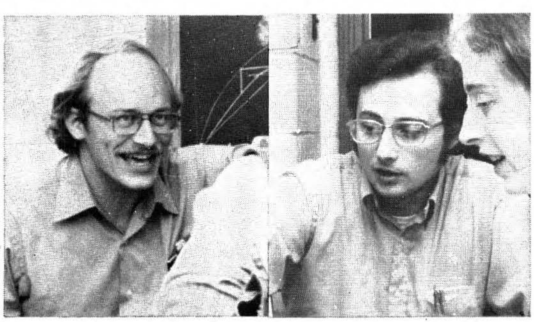

Graduate Study in Chemical Engineering at Rice University

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

The Department has approximately 30 graduate students, predominantly Ph.D. candidates. There are also several post-doctoral fellows and research engineers associated with the various laboratories. Permanent faculty numbers 12, all active in undergraduate and graduate teaching, as well as in research. The high faculty-to-student ratio, outstanding laboratory facilities, and stimulating research projects provide a graduate education environment in keeping with Rice's reputation for academic excellence. The Department is one of the leading 42 Chemical Engineering Departments in the U.S., ranked by graduate faculty quality and program effectiveness, according to recent evaluations.

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APPLICATIONS AND INFORMATION

Address letters of inquiry to:

Chairman
Department of Chemical Engineering
Rice University
Houston, Texas 77001

Rice University

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

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With a population of nearly two million, Houston is the largest metropolitan, financial, and commercial center in the South and Southwest. It has achieved world-wide recognition through its vast and growing petrochemical complex, the pioneering medical and surgical activities at the Texas Medical Center, and the NASA Manned Spacecraft Center.
Houston is a cosmopolitan city with many cultural and recreational attractions. It has a well-known resident symphony orchestra, an opera, and a ballet company, which perform regularly in the newly constructed Jesse H. Jones Hall. Just east of the Rice campus is Hermann Park with its free zoo, golf course, Planetarium, and Museum of Natural Science. The air-conditioned Astrodome is the home of the Houston Astros and Oilers and the site of many other events.

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For Information For further information and a descriptive brochure, write D.D. Edie, Graduate Coordinator, Department of Chemical Engineering, Clemson University, Clemson, SC 29631.

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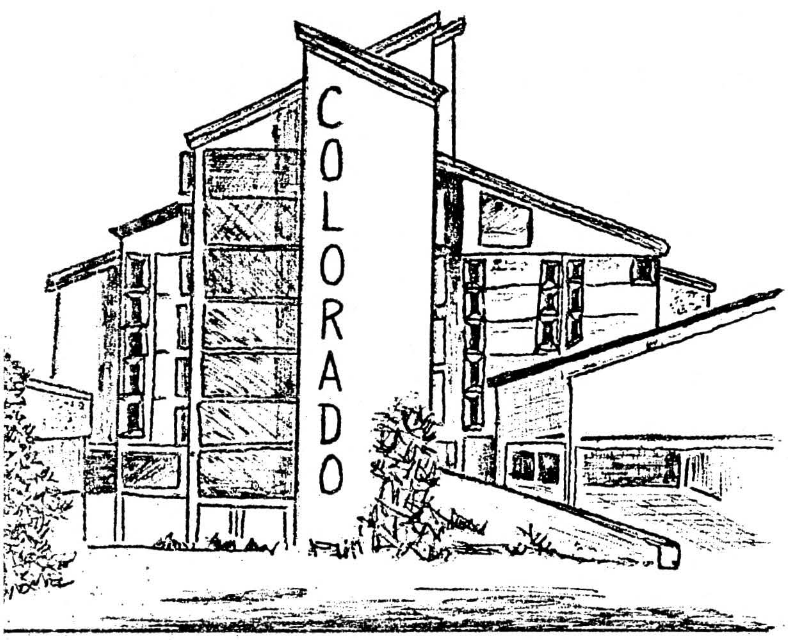

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For application and information, write to:
Chairman, Graduate Committee
Chemical Engineering Department
University of Colorado
Boulder, Colorado 80309

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Department of Chemical Engineering
Whitaker Laboratory, Bldg. 5
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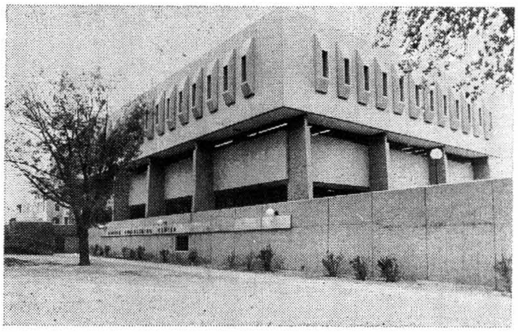

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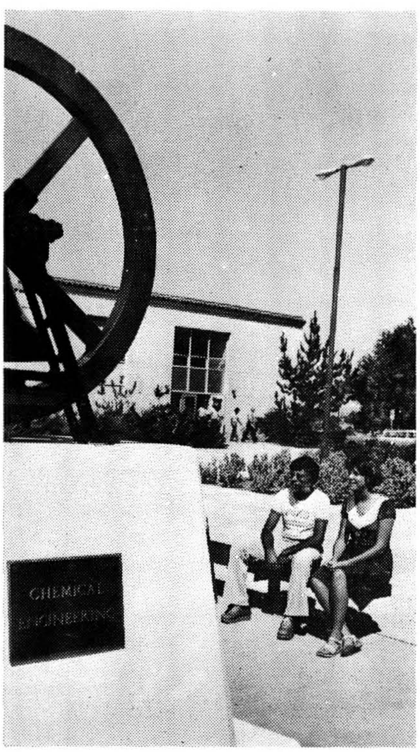

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Director of Graduate Studies
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Rensselaer Polytechnic Institute, Troy, New York 12181.

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CHEMICAL ENGINEERING

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Admissions Chairman
Department of Chemical Engineering
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Stanford, California 94305.

Closing date for applications is Feb. 15, 1978.

FACULTY:

ANDREAS ACRIVOS (Ph.D., 1954, Minnesota)
Fluid Mechanics.

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CURTIS W. FRANK (Ph.D., 1972, Illinois)
Polymer Science.

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ROBERT J. MADIX (Ph.D., 1964, U. Cal-Berkeley)
Surface Reactivity.

DAVID M. MASON (Ph.D., 1949, Cal Tech)
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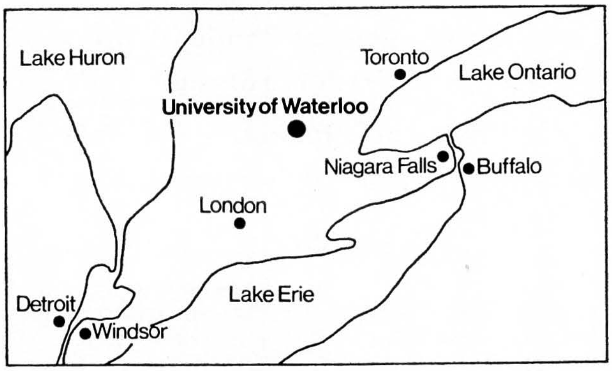

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To apply, contact:

The Associate Chairman (Graduate Studies)
Department of Chemical Engineering
University of Waterloo
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Further information: See CEE, p. 4, Winter 1975

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ERDA: The Department of Chemical Engineering and the Grand Forks Energy Research Center offer a cooperative program of study related to coal technology. Course work is taken at the University and thesis research performed at the Center under ERDA staff members. Fellowships are available to U.S. citizens.

FOR INFORMATION WRITE TO:

Dr. Thomas C. Owens, Chairman
Chemical Engineering Department
University of North Dakota
Grand Forks, North Dakota 58201

ACKNOWLEDGMENTS

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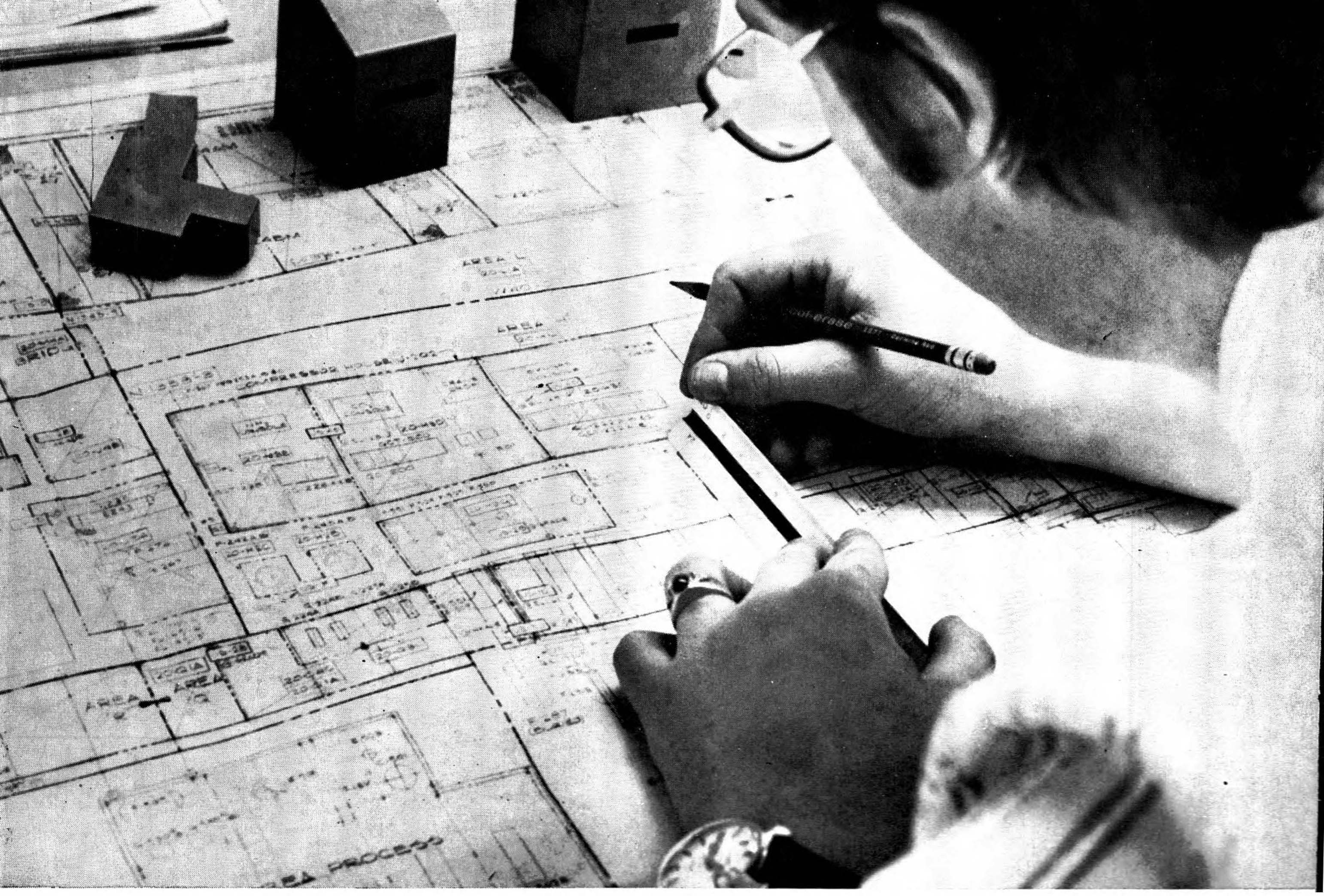

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