



CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

GRADUATE EDUCATION ISSUE

AMERICAN UNIVERSITY GRADUATE WORK

a lecture by

Neal R. Amundson

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A LETTER TO CHEMICAL ENGINEERING SENIORS

As a senior you may be asking some questions about graduate school. In this issue, we attempt to assist you in finding answers.

Should you go to graduate school?

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

What is taught in graduate school?

In order to familiarize you with the content of some of the areas of graduate chemical engineering, we are continuing the practice of featuring articles on graduate courses as they are taught by scholars at various universities. We strongly suggest that you supplement your reading of this issue by also reading the articles published in previous years. If your department chairman or professors cannot supply you with the latter, we would be pleased to do so at no charge.

What is the nature of graduate research?

In an effort to acquaint you with some of the areas of research in chemical engineering, we are also publishing articles on the research of certain faculty members. These articles, as well as those on course work, are only intended to provide examples of graduate research and course work. The professors who have

written them are by no means the only authorities in those fields, nor are their departments the only departments which emphasize that area of study.

Where should you go to graduate school?

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

But wherever you decide to go, we suggest that you explore the possibility of continuing your education in graduate school.

Sincerely,

RAY FAHIEN, Editor *CEE*
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AMERICAN UNIVERSITY GRADUATE WORK*

NEAL R. AMUNDSON
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Houston, TX 77004

A UNIVERSITY PROFESSORSHIP in a good graduate research department can be the best of all possible worlds. Nowhere else does the recipient have such freedom to do as he pleases, a freedom he has earned presumably by good works—teaching, research, publication, and good citizenship—both on the academic scene and outside.

The relationship between PhD adviser and graduate student is a unique kind of relationship that obtains nowhere else to my knowledge. It is an improvement on the father-son** relationship, for there is less stress, no competition, and resolution of problems without trauma. The PhD adviser follows the career and success of his advisee with great pride and suffers as much as a father when that success is not forthcoming. It is a very enduring relationship, and I know of no other comparable one.

What I have just described is the ideal for which many of us strive. Yet, for some, it is a difficult path to trod, for other things get in the way and interfere with its fulfillment. Not all advisers and not all professors are capable or willing to participate in the venture, or understand, in fact, what is involved in proper PhD training. Other matters and goals interfere and thus many may miss what can be an extremely exhilarating experience.

Not all of it is wine and roses. The road can be a rocky one at times, for standards must be upheld, and

The PhD adviser follows the career and success of his advisee with great pride and suffers as much as a father when that success is not forthcoming. It is a very enduring relationship, and I know of no other comparable one.

*Reprinted with permission from *Parameters*, Spring 1987, Cullen College of Engineering, University of Houston.

**This is a personal account, and I have never had an academic father-daughter relationship.



Neal R. Amundson is the Cullen Professor of Chemical Engineering and a professor of mathematics at the University of Houston. He received his BChE (1937), his MS (1941), and his PhD (1945) from the University of Minnesota, where he also served as a faculty member from 1939-1977 and as head of chemical engineering from 1949-1974. He is the author of numerous papers and six books, including *First Order Partial Differential Equations*, Vol. II. He has been the recipient of many awards.

the research that is done must stand the scrutiny of one's peers.

For example, it is not easy to tell one's graduate student of a few years that the work done thus far does not constitute an acceptable thesis. It is even more difficult to tell him after two or three years that, at the rate he is progressing, he probably will never finish a satisfactory dissertation. These are traumatic times for the student, when his perceived career must suddenly detour to some other goal.

It is even more difficult for Professor X to tell Professor Y that the thesis of the latter's student does not meet the standards of the profession. Such a disclosure is often more a criticism of Professor Y than it is of his student.

One of the most critical and important decisions a department can make is whom to admit to a PhD program, for once admitted, most students plan on getting a degree. Since these are very good students, failure for them would be a new experience, an experience to which some of them have difficulty accom-

modating. Usually, departments are too generous in their admissions policy, and future problems are born which rest on the shoulders of the individual adviser.

Normally, a graduate student chooses his adviser at the end of his first year of graduate study during which he has sat through lectures, worked problems, attended seminars and colloquia, and has, perhaps, had casual interaction with some of the faculty at social functions. If he's the average new graduate student, he has chosen his graduate school after visits to a few places—for at most a day—during which he talks briefly with faculty and students. And he obtains some information from his undergraduate teachers.

But, from my experience, this may be unreliable. He probably has looked into the literature little if at all, and since chemical engineering textbooks are notorious in their lack of original literature references, he probably has never heard of anyone at the school he visits. With this paucity of information he chooses a school for graduate study. (Some years ago, while I was head at Minnesota, I decided to inquire of new graduate students why they chose us for their work. Most of the answers had nothing to do with what we presumed was our exalted reputation. One student allowed as how he chose us because we started later than anyone else in the fall, and he wanted to stay in Europe that summer as long as possible. So much for exalted reputations.)

Now we have the graduate student in place, and he must choose an adviser. Students most of the time have a free choice, and that choice is the result of faculty presentations to the whole group of new graduate students and private consultations for those who want more information. In the meantime, the prospective advisee has consulted with current graduate students who give him the lowdown on Professor X who probably, therefore, will get no students. With this mixed bag of information, the student makes a "free" choice. (Random would seem to be a better word.)

Students, of course, almost never ask important questions like: What will be the need for a certain kind of expertise in five years or so when I finish? How successful has Professor X been in placing his students in responsible positions? How many students has Professor X produced, and where are they? Does Professor X work at the front of his field or is he out of it? As a matter of fact, in a good department the problem a student chooses to do for his thesis has little relevance to what he will be doing in a few years, for successful chemical engineers in industry tend to be moved about.

The important thing in a chemical engineering

One student allowed as how he chose us because we started later than anyone else in the fall, and he wanted to stay in Europe that summer as long as possible. So much for exalted reputations.

graduate program is that the student learn the fundamentals of his craft, learn how to do engineering research, and be instilled with confidence so that when he leaves he can be successful either in academia or industry. These things depend upon the way the student has been advised and directed for his degree work and over which the adviser has a great deal of influence. At the beginning, however, the student is naive and thinks that his destiny is in his hands, and his alone. Ah, youth!

The new graduate student is intimidated by the sudden thought that he is now involved in research. He is encouraged by his adviser to read the literature, and that's the way he spends his first summer. He must learn the techniques and methods of his trade. This is less difficult than he imagines, and soon he gains some confidence with the insight that there is less known about everything than he had thought. He still has the nagging idea that if he must know something, it will be out there in a book someplace. The reminder that he is in a research mode now rather than a learning mode, and that what he wants to know has not been done, does not comfort him much.

The student at this stage feels that he cannot compete with all the experts he thinks are out there and whose papers he must read. I suggest to him that there are not so many out there and that, when he finishes his dissertation, he is going to wonder where the experts all went, for then he will know more about that topic than anyone else.

In most cases, as the student progresses through the second and third years, he is struggling. The experiment either does not work or the theoretical analysis is more than he can handle, and the adviser plays a crucial role in guiding him and giving him encouragement and advice, suggesting ideas when they are needed. There is a small class of students who whistle through this period with little advice and counsel from the adviser, and the adviser's main function is to get out of the way. Such students recognize early what they want to do, they have no lack of ideas, and their later success is assured.

The other class of students are those who need a partnership arrangement with the adviser. They are good students of high quality, but for a long time require that the adviser direct their work in detail, telling them where to go and what to look for and what

During all of this travail, the adviser must think of the welfare of the student. The adviser does harm to the student if he uses him in the laboratory as a pair of hands on a fixed piece of equipment or as a computer algorithm for a theoretical thesis. The PhD student is supposed to have contributed to knowledge in some way, and that means *he* contributed. One does him no favors by allowing him to do less.

to do if they find it. With students of this class there is a problem, for they must be told that the thesis is their thesis, and if they mean to be called doctor, they must earn it.

My usual procedure is to be very patient until a time arrives when it is necessary to say that I do not want to confer with them again until they can tell me something about their research that I did not know. "In fact," I say, "next time you come for a thesis discussion, I want to be surprised." One former advisee characterized this as being thrown in the water—swim or learn to swim or else.

While this may seem cruel, it is an astoundingly successful ploy, for almost everyone responds to it well. Students who, up to that point, have never presented an original idea suddenly blossom. A few do not respond and unfortunately receive their degrees without contributing much, and their later careers show that they probably should not have made the attempt.

Those who learn to swim leave the institution with a great deal of confidence and become more successful than they might have otherwise. A problem here resides in the fact that undergraduate and new graduate students are seldom asked to do a synthesis or are challenged in a situation where a novel idea is needed. Research, therefore, thrusts them into a wholly new mode.

During all of this travail, the adviser must think of the welfare of the student. The adviser does harm to the student if he uses him in the laboratory as a pair of hands on a fixed piece of equipment or as a computer algorithm for a theoretical thesis. The PhD student is supposed to have contributed to knowledge in some way, and that means *he* contributed. One does him no favors by allowing him to do less. He should be proud of his thesis upon its completion.

From the advisers view, there is always one more experiment to run or one more calculation to make on a thesis, and he treads a fine line before using the student for his own ends. The greatest PR a department can promote is to have students say when they leave, "I'm happy I came!"

Most PhD students go on to other things after their degrees, whether in academia or industry. In academia many of them continue to work in the area in which they did their theses, much to the chagrin of the adviser, for then he has once again produced still

more competitors and has probably supplied the ideas that will be exploited for a time by the former students.

But this is a short-lived phenomenon, and the former students soon become interested in other things. It is rare in industry for a new PhD to work long in the area of his thesis, since the successful industrial chemical engineer must be flexible. For this reason, the choice of a particular thesis topic is probably the least important of the many other factors involved in good graduate study.

Unfortunately, engineering departments are seldom composed of large numbers of the kind of research advisers alluded to above. Universities are strange places, and they attract their own particular kind of strange characters.

Though the freedom allowed at universities is unlimited, the proper research adviser uses this freedom in the pursuit of proper academic goals. But the freedom is abused, since the fetters applied to academics under the name of academic freedom are rather tenuous. A faculty member may spend too much time in consulting and entrepreneurship, seeking financial rewards the academic pursuit will not provide. He gains financially but loses the respect of his colleagues. This is not a wide class, but it exists and does no credit to the institution.

In a well-run department there is a certain spirit, a spirit difficult to imitate, initiate, develop, even to maintain. Faculty must have respect for each other both publicly and privately. The departments that seem to work best are those in which faculty members are also friends, and this requires personality traits more highly developed than in the general population. Regrettably, good collaborations among faculty are rare, occurring far less frequently than outsiders might imagine.

There is severe competition for research space, new graduate students, money for research equipment and supplies, choice teaching schedules, and more. In a university there is always a finite, too small pool of everything, and the selfish individual can be a problem. It is no wonder that in some departments rancor and cancer exist.

I was always proud of the Minnesota department, since they were class chaps (there were no women at that time) who always thought in terms of what was best for the department—a rare commodity indeed.

We called it good university citizenship, a term little practiced in some places. There is no room in a good operation for those who think of every action, how does it affect me? This soon leads to discord, and in a small group it is disastrous.

The Minnesota department had an amazing success, since the sum of its parts was much greater than the whole, not only because of strong intra- and inter-departmental cooperation, but because of the superb personalities that inhabited the place. I think this was in large measure responsible for its almost complete dominance of the chemical engineering scene for the last twenty years. It is not thus all over.

For many years, there were three leading chemical engineering departments: at Wisconsin, and at two other large institutions. Wisconsin maintained its position over the years because it kept its eye on academic excellence. The other two suffered from similar problems—too much consulting, too much entrepreneurship, too little attention to scholarship, and too much inbreeding. One of these is recovering, but at a time when recovery is difficult.

When one carefully examines academic departments, some difficult questions can be posed. Why is it that some departments, which absorb an enormous

number of new graduate students each year, produce relatively few successful PhD's? Why is it that departments of so-called lesser rank almost never (I'm tempted to say never) produce a world class practitioner? Why is it that some presumably eminent faculty members have never produced a really outstanding PhD?

The opportunities for outside activities are so manifold and the amount of money to be made so great that the temptations are more than some in academia can absorb. A really successful PhD adviser with a good stable of students cannot dissipate his efforts outside the enterprise. The rewards for superior research of both quality and quantity and the satisfaction obtained from the success of former students remain mostly intangible, although the academic community has belatedly come to recognize quality.

In no place is graduate work so readily available and run so efficiently and effectively as it is in the United States; it is truly one of the great developments of this country. In France, Germany, England, and Russia, the mechanisms are much different and far less attractive.

American university graduate work is unique in the world. I'm very happy and proud to have been a part of it for over forty years. □

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A course in . . .

MASS TRANSFER WITH CHEMICAL REACTION

W. J. DECOURSEY

University of Saskatchewan

Saskatoon, Saskatchewan, Canada S7N 0W0

INDUSTRIAL USE OF absorption and stripping in cases where simultaneous homogeneous chemical reaction has an appreciable effect on the rate of mass transfer goes back at least fifty years to the introduction of ethanolamine solutions to absorb hydrogen sulfide and carbon dioxide from gases. Theoretical development in this area goes back about the same length of time to the pioneering studies of Hatta [1, 2]. However, as in many other areas, industrial development had to run ahead of theory; design was based on empirical studies and scale-up. The first reference books devoted entirely to mass transfer with chemical reaction appeared in 1967 [3] and 1970 [4].

I began to teach a graduate course in mass transfer in 1964. The content of that course has been modified considerably in the intervening years. It always contained some mass transfer with chemical reaction, but the content in that area increased appreciably after the book by Danckwerts [4] was published. In recent years, mass transfer with chemical reaction has become the dominant section of the course.



W. J. DeCoursey received his bachelor's degree from the University of Alberta and his PhD from Imperial College, University of London, England, both in chemical engineering. After five years with Sherritt Gordon Mines Limited in Alberta, he spent a year in graduate study at the Massachusetts Institute of Technology. He has taught chemical engineering at the University of Saskatchewan since 1961.

. . . industrial development had to run ahead of theory; design was based on empirical studies and scale-up. The first reference books devoted entirely to mass transfer with chemical reaction appeared in 1967 and 1970.

COURSE CONTENT

The main topics included in the present course and the approximate distribution of time are shown in Table 1.

1. Mathematical Models of Mass Transfer • This topic deals with some basic principles. We consider diffusion equations, diffusivities, and diffusion of electrolytes. This consideration results in differential equations of various degrees of complexity based on various assumptions. Next comes mathematical development of the most important models of convective mass transfer: the film model of Whitman and Lewis, the penetration model of Higbie, and the surface renewal model of Danckwerts. The relation of the Danckwerts model, with its exponential distribution function, to the Laplace transform is discussed. We examine the available experimental evidence regarding the relative accuracy of predictions from the three basic models of convective mass transfer.

2. Enhancement of Mass Transfer Rates by Homogeneous Chemical Reaction • We begin this topic with a simplified form of the diffusion equation with chemical reaction

$$D_A (\partial^2 [A] / \partial x^2) - (\partial [A] / \partial t) - r_A = 0 \quad (1)$$

and a simplified form of Fick's Law

$$N_A = - D_A (\partial [A] / \partial x) \quad (2)$$

These equations are used in subsequent development. The rate of diffusion of component A at the interface between liquid and gas is related to the mass transfer coefficient for A according to the various models. The enhancement factor, E, is defined as the ratio of the time-mean flux of A at the interface with

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TABLE 1
Course Content

TOPIC	APPROX. NO. OF LECTURE HOURS
A. Mathematical Models of mass transfer	5
B. Enhancement of mass transfer rates	18
C. Gas-liquid systems with chemical reaction	6
D. Industrial examples	3
E. Students' presentations	3

reaction to the time-mean flux of A at the interface without reaction but with the same driving force and the same hydrodynamic conditions. This reduces to the ratio of mass transfer coefficients with and without chemical reaction.

In cases where the enhancement factor is appreciably more than one, several studies [5, 6, 7, 8] have shown that in normal industrial equipment, the chemical reaction rate must be large enough so that the composition in the bulk of the liquid is very close to equilibrium. If the reaction is irreversible, that means that concentration of component A from the gas phase is effectively zero in the bulk of the liquid. This simplifies one of the boundary conditions to Eq. (1).

Hatta's analysis is still applicable to the simplest cases, absorption with instantaneous irreversible reaction and absorption with first-order irreversible reaction, both according to the film model. Although combination of Eq. (1) for first-order reaction with the film model, Higbie model, and Danckwerts model respectively gives expressions for the enhancement factor which are widely different in mathematical form, it is quite remarkable how closely the results agree numerically when they are put in terms of Brian's general parameter M [9] or the equivalent

TABLE 2
Effect of Increasing Reaction Rate

For mass transfer with second-order reaction,
 $A + zB \rightarrow \text{products}$

Reaction Rate	$[B]_i$	Reaction zone	Enhancement Factor
Slow	$[B]_o$	negligible	~ 1
Pseudo-1st-order	$[B]_o$	broad region	E_{1st}
Intermediate	$<[B]_o, >0$	region	$> E_{1st}, < E_a$
Instantaneous	0	plane	E_a

Hatta number. The asymptotes for large or small values of M by the various models are identical, and predictions of first-order enhancement factors from the three models agree within 8.1% of the largest prediction, which comes from the Danckwerts model. Such agreement is extraordinary when the different assumptions of the three models are considered.

Second-order reactions of the type

$$r_A = k[A][B] \quad (3)$$

simplify to pseudo-first-order reactions when the depletion of component B (from the liquid phase) becomes negligible at the interface with the gas phase. This corresponds to a comparatively slow reaction, or a small value of the Hatta number. On the other hand, the asymptotic limit for a second-order reaction at high reaction rate is an instantaneous reaction. Thus it is reasonable that expressions for the enhancement factor for second-order irreversible reactions should

The principal mathematical difficulty in obtaining an expression for the enhancement factor for second-order reactions is that the rate expression makes the differential equation non-linear. In fact, there is a non-linear differential equation for each chemical species.

reduce to expressions applicable to pseudo-first-order reactions at small values of the Hatta number and to expressions applicable to instantaneous reactions at large Hatta numbers. A chart for comparison is shown in Table 2.

The principal mathematical difficulty in obtaining an expression for the enhancement factor for second-order reactions is that the rate expression makes the differential equation non-linear. In fact, there is a non-linear differential equation for each chemical species. Van Krevelen and Hoftijzer [10] found an approximate solution for the irreversible case and the film model by two modifications. First they combined the differential equations for species A (from the gas) and B (from the liquid) to eliminate the non-linear rate term, and then integrated to obtain a bridging expression relating the concentration of component B in the liquid bulk and at the interface. Then, realizing that the reaction rate closest to the interface has the largest effect on the enhancement factor, they took the concentration of B in the reaction term as equal to its interfacial concentration independent of distance from the interface. This gave a linear differential equation which could be solved by standard methods. The approach of van Krevelen and Hoftijzer has been applied also to enhancement factors by the Danckwerts

model, both for irreversible [11] and reversible [12] second-order reactions.

Other sub-topics discussed under enhancement include extension to other kinetic forms and relations for reversible reactions. Desorption with reaction is found to be similar to absorption with reaction, but with some important differences [13]. Liquid extraction with chemical reaction is also similar. Non-isothermal enhancement factors are important in cases where temperatures vary appreciably between the bulk of the liquid and the interface. The Marangoni effect gives extra enhancement in some cases. Scale-up from laboratory or pilot-plant experiments is an important area in practice.

3. Gas-Liquid Systems with Chemical Reaction •

The ideas of total molarity and degree of saturation, as introduced by Astarita and Savage [13, 15], are discussed and applied to chemical equilibrium. These concepts are applied also in developing an operating line equation suitable for systems involving chemical reaction. Design relations for a packed column are derived, and an example design problem is discussed.

4. Industrial Examples • The chemistry of a few important cases, such as reactions of carbonates or ethanolamines with hydrogen sulfide or carbon dioxide, is discussed briefly.

ASSIGNMENTS

As you might expect, the course includes frequent problem assignments to illustrate the theory and its applications. A longer assignment toward the end of the course involves design of a packed column for a particular separation. Some results for mass transfer coefficients without reaction and for interfacial areas, calculated from the equation of Onda *et. al.* [16], are given to the students to reduce the amount of time they must spend on the problem.

A term paper is an important part of the course. It is intended to bring students into contact with recent literature and to promote a critical attitude toward the literature. It is to be a critical review of a recent paper, pointing out weaknesses in a chosen paper from the literature, clarifying its application, or extending its scope. Each student submits a written term paper and presents it orally to the class.

REFERENCE BOOKS

The main references used in this course are shown in Table 3. Cussler [17] has produced an excellent book on topics related to diffusion. The present course uses

TABLE 3
Main Reference Books

- A. **Mathematical models of mass transfer:** Cussler [17]; Bird, Stewart, Lightfoot [18]
- B. **Enhancement of mass transfer rates:** Danckwerts [4]
- C. **Gas-liquid systems with chemical:** Astarita, Savage, Bisio [15]
- D. **Industrial examples:** Astarita, Savage, Bisio [15]

only a small part of the material in this book. Some topics from the standard reference by Bird, Stewart, and Lightfoot [18] are used.

Teachers and researchers are divided on the best approach to the theory of enhancement factors. Some prefer the approach of Astarita [3, 15], while others prefer the approach of Danckwerts [4]. Personally, I find Danckwerts more direct and logical.

The book by Astarita, Savage, and Bisio [15] is the only one which introduces the ideas of total molarity and degree of saturation. However, I find some inconsistencies in this book, and its lack of many references in my opinion makes it not very useful for a graduate course.

For recent developments students must be referred to the original articles in the literature.

CONCLUSION

Although many mass transfer devices involving homogeneous chemical reaction are still designed on a strictly empirical basis, often with large factors of safety to allow for areas of ignorance, the theory has advanced now to the point where it is of considerable use in practice. Edwards [10] has pointed out some of the applicable material. Thus there is a need for graduate courses in this area.

NOMENCLATURE

[A], [B]	Concentrations of chemical species
D_A	Diffusivity of component A
E	Enhancement factor
E_{1st}	Enhancement factor for first-order reaction
E_a	Enhancement factor for instantaneous reaction
Ha	Hatta number, \sqrt{M}
k	Second-order chemical rate constant
k_L^*	Mass transfer coefficient without reaction
M	$D_A k [B]_o / (k_L^*)^2$
N_A	Flux of component A
r_A	Reaction rate of A per unit volume of solution



CHEMICAL ENGINEERING DIVISION ACTIVITIES

TWENTY-FIFTH ANNUAL LECTURESHIP AWARD TO JAMES J. CHRISTENSEN

The 1987 ASEE Chemical Engineering Division Lecturer is James J. Christensen of Brigham Young University. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. The 3M Company provides the financial support for this annual award.

Bestowed annually upon a distinguished engineering educator who delivers the annual lecture of the Chemical Engineering Division, the award consists of \$1,000 and an engraved certificate. These were presented to James Christensen at a banquet on August 12, 1987, at the Summer School at Southeastern Massachusetts University. The award is made on an annual basis, with nominations being received through February 1, 1988. Your nominations for the 1988 lectureship are invited. They should be sent to Donald K. Anderson, Michigan State University, East Lansing, MI 48824-1226.

EDITORS NOTE ADDED IN PROOF: CEE has learned that Professor Christensen died suddenly at his home on September 5, 1987. We mourn his loss.

NEW EXECUTIVE COMMITTEE OFFICERS

The Chemical Engineering Division officers for 1987-88 are: Chairman, **John Sears** (Montana State University);

Past Chairman, **Phillip C. Wankat** (Purdue University); Chairman Elect, **James E. Stice** (University of Texas); Secretary-Treasurer, **William E. Beckwith** (Clemson University); Directors, **Gary Poehlein** (Georgia Institute of Technology), **Conrad Burris** (Manhattan College), **Richard M. Felder** (North Carolina State University), and **Lewis Derzansky** (Union Carbide).

AWARD WINNERS

A number of chemical engineering professors were recognized for their outstanding achievements. The George Westinghouse Award was presented to **John H. Seinfeld** (California Institute of Technology) to acknowledge his commitment to excellence in education and his many contributions to the improvement of teaching methods for engineering students.

C. Stewart Slater (Manhattan College) and **A. K. M. Uddin** (Trinity University) received the Zone I and Zone III (respectively) New Engineering Educator Excellence Awards. The awards are presented to non-tenured educators in the first six years of their appointment in recognition of superior performance in teaching and research.

Louis Theodore (Manhattan College) was honored with an AT&T Foundations Award, presented to outstanding teachers of engineering students, and the grade of ASEE Fellow Member was conferred on **James E. Stice** (University of Texas) in recognition of his many important contributions in the field of engineering education.

CORCORAN AWARD TO R. BYRON BIRD

R. Byron Bird (University of Wisconsin) was the recipient of the second annual Corcoran Award, presented in recognition of the most outstanding paper published in *Chemical Engineering Education* in 1986. His paper, "Hougen's Principles," appeared in the fall 1986 issue of CEE.

t Time
x Distance from the interface
overbar Time-mean value

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1987 SUMMER SCHOOL

G. L. SCHRADER, M. A. LARSON
Iowa State University
Ames, IA 50010

The 1987 Summer School for Chemical Engineering Faculty, arranged through the Chemical Engineering Division of the American Society for Engineering Education, was held on August 9-14, 1987, at Southeastern Massachusetts University, North Dartmouth, Massachusetts. Over 350 attendees were present at the meeting, representing 113 universities in the United States and Canada and several European and Australian schools. Sixteen industrial sponsors (see Table 1) contributed nearly \$100,000 to assist in the planning of the program, local expenses, and costs for instructor and faculty member participation. It was the tenth Summer School in a series begun in 1931.

The theme of the 1987 Summer School was the revitalization of the chemical engineering curriculum in response to the changing technological needs of modern society. Five plenary sessions were held to discuss some of the broader implications of these changes. Four blocks of workshops were organized around specific themes: Emerging Technology (G. L. Schrader, Iowa State University), Computers and Computation in Chemical Engineering Education (H. S. Fogler, University of Michigan), Applied Chemistry in Chemical Engineering (J. W. Schwank, University of Michigan), and Curricula, Courses and Laboratories (J. C. Friedly, University of Rochester). Forty-four faculty members and industrial speakers served as instructors for the meeting, all donating their time and effort.

The first plenary talk addressing the general future curriculum directions in chemical engineering was given by Professor James Wei of the Massachusetts Institute of Technology. Professor Wei discussed the important need for a new paradigm in the curriculum, such as were provided by the unit operations and transport phenomena directions in the 1920s and 1960s. Because of the loss of important sectors of America's industrial economy, there has been a general concern regarding engineering education in the United States, and there are strong pressures for chemical engineers to become involved in new technological areas. Within traditional courses, there are opportunities to introduce new emphases or problems at the micro-, meso-, and macroscale at which chemical engineers are accustomed to work. For example, instead of dealing only with small molecules, gases and homogeneous liquids, large molecules, complex liquids and solids should be addressed; rather than being concerned exclusively with inorganic or organic chemistry applications, biochemistry, material science, and condensed state physical chemistry should have a role in

chemical engineering courses. Professor Wei provided a number of specific curriculum suggestions, among which was the discussion of a product engineering course which would explore the relation between molecular configuration and aggregation and product quality. The design and synthesis of materials with specific performance in use could also be included in traditional design courses. Also proposed were courses in surface and colloid chemistry, electronic materials processing, biotechnology, and solid state chemistry. The new technological demands made on the chemical engineering profession may lead to need for new educational plans and degree requirements. Professor Wei pointed to the difficulty of cramming more courses or course content into the four-year BS degree and to the decline of the industrial "apprentice" format as traditional industry reduces senior staff, leaving fewer experienced engineers to teach incoming graduates. This is coupled with an information explosion which has made it increasingly difficult for all levels of engineers to be technically well-informed. Professor Wei called for a new consensus among academic and industrial engineers in which the first professional degree (four-year BS) is regarded as being suitable for light technical work such as marketing, administration, technical personnel, or production planning. To be effective in heavy technical work such as design, process development, consulting, and construction, the student should obtain a MS degree or secure a significant apprenticeship with an experienced senior engineer.

Dr. Stanley Proctor of Monsanto discussed "Biotechnology and Chemical Engineering Education" in the second plenary session. The value of products from biotechnology is projected to grow enormously by the year 2000, with major opportunities coming in human health care, crop science, and waste management. Dr. Proctor stated that chemical engineering is a good base from which the student can expand into the biotechnology area, specifically by the addition of life science courses such as microbiology, biochemistry, and biochemical engineering unit operations. Biotechnology can also be introduced into the core courses of chemical engineering with subjects such as bioreaction engineering and bioprocessing purification and separation. There is a need for laboratories suitably equipped for life science studies, with the appropriate unit operations and instrumentation. It is especially helpful to use laboratory assistants with life science backgrounds, as well as having faculty members with life science training. Dr. Proctor raised the difficulty of doing this in a four-year program, but suggested improving the curriculum flexibility, incorporating biotechnology into existing courses, reducing duplication, and eliminating credit for courses which are prerequisite for program admission. Dr. Proctor projected that the largest need for BS/MS

New Directions in Chemical Engineering Education

TABLE 1
Industrial Sponsors

American Cyanamid Company
Amoco Oil Company
BASF Corporation
Chevron Corporation
Dow Chemical U.S.A.
Dow Corning Corporation
E. I. du Pont de Nemours & Company
EXXON
Merck, Sharp & Dohme Research Labs
Phillips Petroleum
PPG Industries Foundation
Shell Development Company
Tektronix
The Standard Oil Company (SOHIO)
3M
Union Carbide Corporation

biotechnology graduates focused on design and operation will come after 1990.

The opportunities for chemical engineers in high technology materials processing was addressed in two plenary sessions presented by practicing chemical engineers. Dr. Michael Bohrer of AT&T Bell Laboratories discussed "Chemical Engineering in Electronic Materials Processing." Chemical engineers have made substantial contributions to modern silicon and optical fiber manufacturing technology. The core curriculum has served chemical engineers well for working in the electronics industry, as reflected by the rapid increase in the hiring of BS chemical engineers. Students should be exposed to a broad range of problems; courses in material science and solid state physics should also be included.

Dr. Kenneth McKelvey of Dupont addressed some of the important technological problems associated with the design and manufacture of advanced materials and composites. The microstructure of these materials must be very carefully engineered since the interfacial region frequently involves two incompatible materials. There are important technological opportunities in developing more engineered microstructure materials, liquid crystalline polymers, and electrically conductive polymers. Dr. McKelvey stated that chemical engineering education frequently does not take the interdisciplinary approach used by industry and this can be a serious drawback. Chemical engineers do have a unique approach to problem solving which frequently begins with a phenomenological description in areas such as transport

phenomena, kinetics, and thermodynamics. This is followed by a quantifying and modeling approach. Dr. McKelvey pointed to a reduced hiring pattern for chemical engineers by companies that are forming special expertise in the advanced materials area.

The final plenary speaker was Professor Warren Seider of the University of Pennsylvania. Professor Seider spoke on "Chemical Engineering and Instructional Computing—Are They in Step?" Transitions in chemical engineering courses and advances in instructional computing were examined. Developments in optimization, micro-computer software, and expert systems for teaching the design and control of conventional and unconventional processes were detailed. New developments to introduce "open-ended," design-oriented computing lessons in courses other than process design and process control were described. In addition, examples of more advanced concepts in undergraduate courses were presented, including reactor stability analysis, thermodynamics in the critical region, and mass transfer in separators. Questions concerning the minimal requirements for computation in the accreditation of chemical engineering curricula were discussed. Professor Seider concluded that the instructional material for design and control courses are in step with the technology represented by conventional processing, but that there needs to be an improvement with respect to the more recent technological interests of chemical engineering.

Workshop sessions were held in the mornings and evenings and provided an informal atmosphere for faculty members to exchange specific information about coursework development. Poster sessions were held in the afternoon, permitting up-to-date presentations of materials by the participants. Over seventy posters were submitted.

On Wednesday, the 3M Award Lectureship was awarded to Professor James J. Christensen, of Brigham Young University, who spoke on "Reflections on Teaching Creativity" and who addressed the essential need of including creativity in the chemical engineering curriculum.

The lecture was followed by the Division business meeting. The Summer School participants also had opportunities to tour the Newport area.

A financial report of the Summer School will appear after the final distribution of subsidies to participating departments (planned for late 1987). Any questions concerning the final preparation of this report should be addressed to the Co-Chairmen.

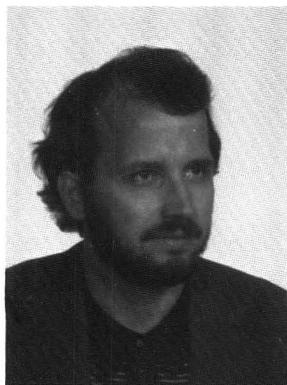
Local arrangements for the Summer School were assisted by Professor L. Bryce Andersen of Southeastern Massachusetts University, and by Professor Stanely M. Barnett of the University of Rhode Island.

A course in . . .

FUNDAMENTALS OF MICROELECTRONICS PROCESSING (VLSI)

CHRISTOS G. TAKOUDIS
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A FIFTEEN-WEEK COURSE in the fundamentals of microelectronics processing has been prepared to meet the needs of graduate and advanced undergraduate students in Purdue's School of Chemical Engineering. There is ample evidence of the impact of large scale integration on calculators and computers. Very large scale integration (VLSI) is bringing about great changes in industrial process control, automotive electronics, and other fields in which data acquisition, computation, or controls are necessary. In recent years, chemical engineers have been increasingly involved in chemical vapor deposition, epitaxial lateral overgrowth, microlithography and silicon growth on insulators. The aim of this course is to teach the basic principles and practical aspects of the most advanced state of electronics processing. The main emphasis is on fundamental processes that are especially useful for VLSI schemes. The course outline is given in Table 1.



C. G. Takoudis received his Diploma (1977) at the National Technical University of Athens, Greece, and his PhD in chemical engineering (1982) at the University of Minnesota. He joined the faculty of Purdue University in November 1981. His research interests are in the areas of reaction engineering, heterogeneous catalysis and microelectronics processing.

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Perhaps the rapid pace of innovation does not fit the limited timetable for publication of a book [1-5]. Recent efforts are most often treated in journal articles and as a consequence, those journal articles end up playing a key role in this course. Some of the articles are mentioned at the end of this paper [6-14].

In order to maintain the pace shown in Table 1, some topics were not covered in depth. For these topics, several references were suggested, and students'

TABLE 1
Course Outline

Introduction
<i>Overview of Microelectronics Semiconductor Devices</i>
Crystal Growth and Epitaxy
<i>Crystal Growth Chemical Vapor Deposition Vapor Phase Epitaxy Molecular Beam Epitaxy Silicon on Insulators Epitaxial Lateral Overgrowth Doping Profiles in Epi-layers</i>
Dielectric and Polysilicon Film Deposition
<i>Deposition Processes Reactor Design Polysilicon and Silicon Dioxide Process Simulation</i>
Ion Implantation
<i>Ion Implant System-Dose Control Impurity Profiles of Implanted Ions Process Considerations</i>
Lithography
<i>Pattern Generation-Mask Making Printing and Engraving Resists Process Considerations</i>
Dry Etching
<i>Selectivity-Feature Size Control Gas Discharges Plasma-Assisted Etching Techniques Process Simulation</i>
Other Processes-Device and Circuit Fabrication
<i>Oxidation Diffusion Metallization Fabrication Considerations</i>

comprehension was examined through homework problems and midsemester exams. At the end of the course, the students expressed approval of the texts (1, 2, 5) and of the supplementary readings.

The course begins with an overview of microelectronics. The major technologies for the manufacture of microcircuits are discussed, and the students become familiar with small-, medium-, large-, and very large-scale integration. After a general discussion of some of the materials used in microcircuits (*i.e.*, Si, Ga, As) the physics of semiconductor devices is briefly covered. Concepts such as energy bands, carrier concentration and carrier transport phenomena are presented, while the students begin familiarizing themselves with the p-n junction and bipolar, unipolar and microwave devices. The basic principles of these devices are also discussed.

The first major step in device fabrication includes crystal growth and epitaxy. The starting materials of semiconductors (*e.g.*, silicon dioxide for a silicon wafer) are chemically processed to form a high purity polycrystalline semiconductor from which single crystals are grown. The growth of crystals from a melt as well as float zone processes is studied in detail. Emphasis is placed on the conceptual understanding and mathematical modelling of such processes.

The growth of a single-crystal semiconductor upon a single-crystal semiconductor substrate, called epitaxy, is closely related to the technology of crystal growth. The epitaxial process offers an important means of controlling the doping profiles so that device and circuit performances can be optimized. Many novel device structures can be made by epitaxial processes [3]. Some important epitaxial growth techniques are discussed, with emphasis on vapor-phase epitaxy and molecular beam epitaxy. The growth of silicon on insulators is covered next. One of the primary aims of the study of such a process is the fabrication of three-dimensional integrated circuits. A conceptual understanding and mathematical modeling of epitaxial lateral overgrowth are emphasized within this context.

To fabricate discrete devices and integrated circuits we use many different kinds of thin films, such as dielectric layers and polycrystalline silicon. Deposited thin films must meet many requirements. The film thickness must be uniform over a large number of wafers processed at one time. The structure and composition of thin films must be controlled and reproducible. Therefore, it is necessary to understand all the variables in the reactor design of a dielectric or polysilicon film deposition. The modeling of reactors used for such depositions is discussed in detail.

The masking structures mentioned previously provide an introduction to the process of transferring patterns of geometric shapes on a mask to a thin layer of radiation-sensitive material covering the surface of a semiconductor wafer.

Ion implantation is investigated next and is one of the key processes we use to introduce controlled amounts of dopants into semiconductors. The specific goals that must be realized in this process are: the energetic charged atoms or molecules should be deposited in the exact quantity specified and to the correct depths below the surface; the deposition should be limited to only the designated areas of the substrate; when required, it should be possible to electrically activate all the implanted impurities; as much as possible, the silicon (or other material) lattice structure should be unchanged by the dopant incorporation process. To meet these goals, a number of approaches are discussed. Models of the different aspects of ion implantation as well as adequate masking structures against the implant are shown to play a key role in the overall process.

The masking structures mentioned previously provide an introduction to the process of transferring patterns of geometric shapes on a mask to a thin layer of radiation-sensitive material (called resist) covering the surface of a semiconductor wafer. This process is called lithography, and such patterns define the various regions in an integrated circuit such as the contact windows, the implantation regions, and the bonding-pad areas. The resist patterns defined by the lithographic process are indicated to be only replicas of circuit features and not permanent elements of the final device. Mathematical modeling of some of the printing and engraving steps in a lithographic process is discussed in detail.

To produce the circuit features mentioned above, the resist patterns must be transferred once more into the underlying layers comprising the device. The pattern transfer is accomplished by an etching process which selectively removes unmasked portions of a layer. Emphasis is given to dry etching techniques that use plasmas in the form of low-pressure gaseous discharges. These techniques are used in VLSI processing because of their potential for very high fidelity transfer of resist patterns. Modeling and process simulation of some dry etching methods are presented in depth. It is important for the students to realize that selectivity and feature size control are key issues in any dry etching technique.

Oxidation, diffusion and metallization are dis-

TABLE 2
Titles of Final Projects in Fall 1985, 1986

- Molecular Beam Epitaxy
- Silicon on Insulators: A Focus on Epitaxial Lateral Overgrowth
- Solid Phase Epitaxy of Silicon
- Gettering
- GaAs Contacts: Theory and Practice
- Review of the Thermal Nitridation of Silicon
- A Comprehensive Study of Plasma Etching Technology
- Optical Resist Systems
- X-Ray Lithography: The Solution to Submicron Device Design?
- Resist Material Considerations for VLSI Edge Definition in Lithography
- Kinetics in the Vapor Phase Epitaxy of GaAs
- Alternatives at the UV Limit of Optical Lithography
- Recent Studies on the Kinetics of Epitaxial Silicon Growth
- X-Ray Lithography
- Metalorganic Chemical Vapor Deposition
- Low Pressure Chemical Vapor Deposition Reactors
- Chemical Vapor Deposition of II-VI Materials
- Low Temperature Deposition of Silicon Dioxide

cussed briefly, either because chemical engineers are already familiar with some of the basic principles of these processes (e.g., oxidation, diffusion) or because many aspects of such processes have been previously covered (e.g., metallization). Also, diagnostic techniques and device and circuit fabrication are briefly discussed. Some emphasis is given to isolation, self-alignment, local oxidation, planarization, and gettering.

The last stage of this course is a final project that is mandatory for all graduate students (and optional for all undergraduates) who take the course. After choosing from a list of topics, each student works on his/her own project. Topics covered in the past two years are listed in Table 2. Within such a project, a student is expected to critically review any existing literature and to present his/her own (perhaps innovative) ideas for improving or developing various processes.

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ChE book reviews

COMPUTER-AIDED ENGINEERING FOR INJECTION MOLDING

Edited by Ernest C. Bernhardt

MacMillan Publishing, New York 10022, 1984

Reviewed by

Donald G. Baird

Virginia Polytechnic Institute

This book is a collection of topics involving the application of computers to the design and control of the injection molding process. Unfortunately, as noted by the editor, the chapters lack coordination and hence the book represents a collection of topics rather than a unified text. However, it is one of the first attempts in the polymer field to develop a complete package starting with the ideas of hardware, process control techniques, the basic equations which are required to simulate injection molding, and the application of computer simulation to solving injection molding problems.

The book is divided into three sections, with the first section being entitled "State of the Technology." The first chapter in this section is rather general in nature and attempts to explain in qualitative terms how the computer is used in the design of injection molds. For example, it is illustrated how a mold designer might use a computer simulation to predict where weld-lines would lie and how the location of cooling channels would change the temperature distribution in a part. Certainly this information is useful, but it does not allow one to accomplish any quantitative design work. The second chapter is also quite qualitative in nature as it describes melt flow in

cavities. This chapter does emphasize the importance of fountain flow to the development of properties and the fact that the properties of a part are related to melt flow. However, there are a number of topics, such as computer hardware and computer languages, which seem to be unconnected to the first part of the discussion and of such elementary level that they serve no practical purpose. For example, the distinction between mainframe computers and minicomputers doesn't seem to be necessary. The third chapter is also of limited value as it attempts to explain how the mold designer might use computer aided design (CAD) but it never specifies what packages are available or gives examples as to how the mold designer could use CAD. Hence, in general, the first three chapters are so descriptive in nature that they serve very little practical purpose.

Following these first three qualitative chapters comes Chapter Four, which presents some of the basic equations which are required in the modeling of injection molding. Although this information is well presented and lends to the understanding of what equations must be solved, there is no connection between this chapter and the rest of the book. Furthermore, the author of the chapter does not explain how these equations are solved on the computer nor how they could be used in computer aided design. Finally, the material reflects mostly the author's view of simulating injection mold filling, and fountain flow is neglected.

Chapter Five is descriptive again and describes how the computer is used in process control. Control is all based on reading some process variable such as mold pressure which must be within some specified range based on previous experience in generating parts with acceptable physical properties. This approach relies on no real knowledge of the mold filling process. The failure to point out the limits of such an approach would be quite beneficial, but this is not done in the chapter.

Chapters six through eleven constitute Part II of the book, which is entitled "Applications." Again, the chapters are not connected nor do they always fit within this heading. Chapter Six discusses how a part is designed through structural analysis, but there is no direct correlation back to mold design. The next chapter discusses (only in a very qualitative sense) mold design. Only one particular CAD/CAM system is described. Chapter Eight is how an integrated approach for the design of an injection molded part should be implemented. Again, the chapter is very descriptive and one has no idea as to the limitations of the approach used by the authors.

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1/2 page \$50; each additional column inch \$20.

VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY

The Chemical Engineering Department at Virginia Tech is seeking applicants for a full time tenure track faculty position. Duties include teaching at undergraduate and graduate levels, establishing and conducting a funded research program, and departmental service. Rank and salary commensurate with qualifications. Virginia Tech has approximately 20,000 undergraduates (5,000 in the College of Engineering, including 170 in Chemical Engineering) and 3,600 graduate students (1,200 in the College of Engineering, including 50 in Chemical Engineering). Send resume and names of three references to Chairman, Departmental Search Committee, Chemical Engineering Department, Virginia Polytechnic Institute & State University, 133 Randolph Hall, Blacksburg, VA 24061. Deadline for applications is January 31, 1988. Virginia Tech hires only U.S. citizens and lawfully authorized alien workers. Virginia Tech is an Affirmative Action/Equal Opportunity employer.

UNIVERSITY OF FLORIDA

Chemical Engineering faculty position: A tenure track position is available for August, 1988, at the University of Florida. The rank and area are open. Applicants should submit a brief resume, a description of research objectives, and the names of three references to: Dr. H. H. Lee, Chairman of Search Committee, Department of Chemical Engineering, University of Florida, Gainesville, FL 32611. The University of Florida is an Equal Opportunity/Affirmative Action employer.

In Chapter Nine, the Mold Flow program and its application to solving molding problems are discussed. This chapter is quite well done and does demonstrate how a simulation can be used to solve molding problems. Again, however, the limits of this program and the range of problems it can handle are not discussed. This chapter should have been placed near Chapter Four. Chapter Ten, which is concerned with mold cooling, is also well-written, but should be grouped with Chapter Four.

The last chapter in section II is concerned with data acquisition and control of the injection molding process. This chapter is of educational value as it ex-

Continued on page 218.

A course in . . .

TRANSPORT PHENOMENA

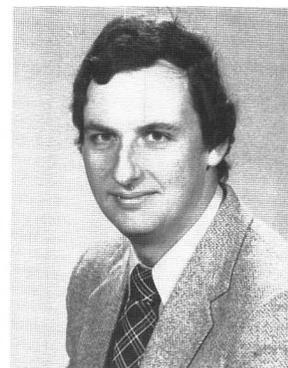
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IF THERE IS ONE subject in which the philosophy of undergraduate instruction at various institutions could be best described as diverse, it is transport phenomena. Topics which fall under this heading may be found in courses titled as unit operations, fluid mechanics, heat and mass transfer, or simply transport phenomena. The content of these courses is as varied as the titles are, with the resulting extremes being students who are either quite knowledgeable in the workings of various pieces of process equipment or who have a grasp of transport processes only on a microscopic level. Consequently, each student entering our graduate program has a different level of understanding of the basic principles governing the transport of heat, mass, and momentum as well as a diversity of the analytical skills which are necessary to solve these problems. The question becomes: How does one teach a single course sequence which all of these students will find interesting and challenging?

At Notre Dame this is done by following a philosophy for a two semester graduate transport phenomena course sequence which we suspect is similar to most other schools. The fundamental principles are explained and emphasized a number of times throughout the course. The skills necessary to solve the requisite differential equations are honed, and a significant amount of time is spent discussing example problems which display both important physical situations and interesting solution techniques.

The principal difference between our courses and those which we have encountered elsewhere is that we have designed the content and order of presentation so as to avoid placing undue hardships on students whose undergraduate education did not emphasize the formulation and solution of partial differential equations. This is done by saving most of the advanced mathematics for the second semester.

The first course strongly stresses the pertinent physics and the correct way to approach an arbitrary new problem, be it micro or macroscopic. When students learn some of the more powerful mathematical techniques for solving problems in heat and mass



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transfer in the second semester, they are able to explore problems involving greater mathematical complexity (such as Rayleigh-Benard convection and fluid flow past a heated sphere) without becoming overwhelmed.

FLUID MECHANICS

The subject of the "Transport Phenomena I" course, which is taught in the fall, is primarily fluid mechanics. In fact, given both of the instructors' research interests, the course could be better titled "Fluid Mechanics." A quick survey of simple macroscopic problems is done so that students who spent their summer in Europe or spinning discs at local dance establishments can reorient themselves to coursework. A homework problem set assigned the first class day includes both easy and difficult problems which are typically discussed in undergraduate courses. From the various complaints, it is possible to judge what topics must be reviewed. (It is interesting to note how many students have difficulty getting the

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correct *number* for pressure drop for turbulent flow in a smooth pipe.)

Lectures begin with a discussion of the kinds of forces which are found in fluid flows and how to describe them mathematically. The stress and strain tensors are introduced along with transformations and index notation. The primary references for this material are the texts by Whitaker [1] and Batchelor [2]. The boundary conditions which arise in various physical situations are then introduced. At this point it is possible to derive the mass and momentum conservation equations. The derivation is done both by shell balance and by using the substantial derivative to convert Newton's second law from a Lagrangian to an Eulerian framework. The conditions under which these equations reduce to the Navier-Stokes equations are examined.

The equations of motion are then used to solve problems in one or more dimensions, first for cases where exact solutions exist. Mathematical techniques such as separation of variables and special functions, which may be new to many students, are introduced in lectures and are used for homework problems.

A quick survey of the kind of fluid flow problems which engineers with advanced degrees may need to solve during their career indicates that not all of them should be approached from the microscopic view. Unfortunately, many students have gotten the idea that the macroscopic momentum equations are useful only to solve homework problems in undergraduate courses; they have the mistaken impression that all *real* problems will yield to a detailed analysis using the Navier-Stokes equations. In addition to not realizing whether differential or integral balances are appropriate, their ability to successfully apply integral balances to other than one dimensional problems is generally limited.

For this reason, lectures which deal with macroscopic problems are inserted at this point. Macroscopic balance equations are derived from the differential equations by the application of the divergence theorem and also by using integral averages of flows and forces on macroscopic control volumes. A typical homework problem might be the derivation of Dressler's equations for flow of a turbulent fluid in channel including the effects of air shear and surface tension. The mechanical "energy balance" is derived from the momentum balance for two reasons. The important concept of dissipation, which accounts for the missing energy, is introduced and the natural link between thermodynamics and fluid mechanics is developed.

This link is further explored when the next subject, compressible flow, is discussed. Compressible

flows occur in numerous physical situations which chemical engineers may encounter, but they seldom receive much attention in courses. (Does the velocity of a gas really *increase* as it flows through a pipe? Why is the gas pump for my experiment not working at its rated flow rate?) When the macroscopic balance equation for total energy is derived and compared to the mechanical energy equation, the physical significance of dissipation in terms of entropy becomes clear. The relation between entropy production and velocity gradients is discussed. The concept of sonic velocity and choking are also introduced.

The focus of the course now shifts to follow what is more commonly taught in graduate transport courses—application of the Navier-Stokes equations to problems where exact solutions do not exist. Creeping flow is done first. The important idea here is that various nonzero terms are neglected not simply be-

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cause they are small, but small in comparison to other terms. The physics of creeping flows is discussed in detail—what does it really mean to have no inertia? It is noted that velocity fields (solutions to Stokes' equations) are superimposable as a consequence of the linearity of the equations.

The solution to the zero Reynolds number equations is done for the sphere, and arguments leading to Stokes' paradox are investigated. The Oseen solution is done and Whitehead's paradox is discussed. At this point the general idea of perturbation solutions is introduced and used to improve the solutions for rotating flows. In addition, the matched asymptotic solution for flow around a sphere is briefly outlined.

The next topic, ideal fluid flow, commences with a description of the physical meaning of irrotationality and situations where it provides an accurate description. The primary source of information for lectures on ideal fluids is gotten from the texts by Streeter [3] and Lamb [4]. The velocity potential function is introduced and used to show that Laplace's equation governs these flows. This leads to the amazing realization that velocity fields are superimposable for ideal flows as a consequence of the absence of shear forces even though the underlying Navier-Stokes equations are nonlinear. The solution of the problem for flow around a sphere leads to d'Alembert's paradox. The idea of

circulation is introduced and the application of ideal fluid theory to the calculation of lift for flow over various bodies (including baseballs, golf balls, and sails) is discussed.

The next topic is boundary layer theory, for which Schlichting's text [5] serves as an invaluable reference. BLT is an especially rich subject to study in a graduate course because all of the many approximations which arise can be shown to follow as obvious consequences of Prandtl's observation that viscous and inertial forces balance near solid boundaries. To show the utility and validity of the various assumptions it is instructive to compare calculations of drag from solutions to the boundary layer equations with data to demonstrate that the approximations do in fact lead to good agreement.

Tests, of which there are usually two in addition to a final, are designed so that students may be creative as well as display a basic level of understanding of the course material. Questions from the most recent semester included the locomotion of cephalopods, flow over porous airplane wings, and wave propagation described by an Orr-Sommerfeld equation. On each test, problems which require either integral or differential balances are interspersed. This requires that students think about which approach is appropriate. After the first course, students are expected to ask the correct questions when confronted with a new problem. They should know how to examine the essential physics on an appropriate scale.

HEAT AND MASS TRANSFER

In the spring, the topics switch to heat and mass transfer. Up to this point the time spent examining macroscopic problems and emphasizing the physics for each situation has limited the number of important analytical methods the students have been exposed to and which may be necessary for solving difficult detailed problems that arise in their research. In the second semester the emphasis on physical principles is retained, but the problems discussed also serve to introduce the students to advanced mathematical techniques.

As in the first semester, the second semester begins with the derivation of the transport equations—this time energy transport—only now the equations are derived using vector notation. A detailed understanding of how the equation of energy works in vector form is built by assigning problems such as the derivation of the rate of entropy production. The text for this material (in addition to the texts used in the first semester) is Bird, Stewart and Lightfoot [6].

Einstein notation is also re-introduced at this point in the course (as it was not used extensively in the first semester), leading to a great simplification in the form of the transport equations.

Following a conventional sequence, steady conduction in solids is reviewed, first assuming constant properties and then relaxing this restriction to include non-constant properties, introducing the student to regular perturbation methods. A supplemental text for perturbation methods is Van Dyke [7], which is further utilized when matched asymptotic expansions are discussed later in the course. The course now turns to the effects of convective energy transport, examining problems such as transpirational cooling and forced convection through a heated pipe. Rather than using a cookbook approach to the Graetz problem, the students are introduced to the formal theory of a Sturm-Liouville eigenvalue problem. Particular emphasis is placed on when to expect this type of solution and how to cast the problem into the Sturm-Liouville form.

Dimensional analysis is the next topic of discussion. However, here we differ from the usual transport class in that dimensional analysis is introduced in the context of the large field of similitude. The references for this material are the notes from a course on similitude taught by Van Dyke [8] which are distributed to the class. Over one week is spent introducing the students to techniques for finding hidden symmetry in physical problems, first through the use of dimensional and inspectional analysis for the reduction of the number of independent parameters involved in a problem and then via more advanced techniques, such as coordinate stretching to achieve reductions in the number of independent variables upon which a problem depends. These techniques are illustrated by examples from both momentum and energy transport, such as the determination of the radius of a shock wave produced by an intense point explosion solved by G. I. Taylor [9], the velocity field of a submerged laminar jet, and such whimsical examples as the spread of a viscous thread of liquid flowing down an inclined plane.

The concept of self-similarity is put to immediate use in the next topic—that of unsteady conduction in solids. In addition to the standard semi-infinite and finite slab problems, a semi-infinite slab with a melting boundary is also discussed. Students are asked to explain why such a problem with a step change in temperature at the edge of the slab admits a similarity solution, but such a solution for a constant heat flux does not exist.

The course next turns to boundary layer theory

for forced convection past a heated, horizontal flat plate. This problem is solved in the limiting cases of large and small Prandtl numbers, and then the plate is turned to the vertical for a discussion of free convection. For homework, students use the concept of self-similarity to solve the analogous problem of a free-convection laminar jet arising from a point source of energy. A general dimensional analysis of the free and forced convection transport equations is inserted at this point so that the students can develop an intuitive feel for the relative magnitude of the two transport mechanisms.

The study of free convection is continued by examination of the instability of a fluid heated from below. The Rayleigh-Benard stability problem for free-free boundaries is discussed in detail, the reference for this discussion being the text on hydrodynamic stability by Drazin and Reid [10]. The students' understanding of the principles of this mathematically complex phenomenon is reinforced by homework in which the stability conditions for problems analogous to the Rayleigh-Benard problem are worked out and also by assignments on a more cosmic scale in which the students solve the Jeans problem for the gravitational collapse of a galactic sized gas cloud.

At this point in the course we begin our discussion of singular perturbation theory, drawing heavily on the text by Van Dyke. First, we examine the classic problem of creeping flow past a heated sphere at small Peclet number solved by Taylor and Acrivos [11]. This problem serves to introduce the concept of a non-uniformly valid first approximation, and why a regular perturbation approach to such problems is doomed to failure. The students are shown how to overcome these difficulties via a matched asymptotic expansion approach which, in this problem, also introduces the student to special mathematical functions such as spherical harmonics and Legendre polynomials. Flow past a sphere is followed up by such problems as flow through a tube with an axial wire and unsteady conduction from an infinite cylinder. The method of reflections comes next, in which we emphasize the similarity of this technique to the singular perturbation methods just discussed and which is used to determine the energy loss from a heated sphere in the vicinity of a plane. The analogous problem of a heated cylinder near a plane, which cannot be solved using perturbation techniques, is also examined and solved using conformal mapping, adding yet another technique for obtaining solutions of the transport equations to the students' arsenal.

Brief discussions of turbulent and radiative transport mechanisms complete the portion of the course

dealing with energy transport. Topics discussed here include Prandtl mixing length theory and transport correlations in turbulent systems, together with the concepts of isotropy, black and gray bodies, view factors, an introduction to configurational algebra and spectral effects in radiative energy transport.

With three weeks remaining, the course turns towards mass transport. The first two lectures are devoted to definitions, the description of mass transport in terms of Fick's Law, and derivation of the transport equations. Simple problems come next, such as the Stefan tube and diffusion with homogeneous or heterogeneous chemical reaction (the Thiele problem). Combined mass, momentum and energy transport in boundary layers is discussed in which the effect of mass transport on the evolution of the thermal and momentum boundary layers is examined. Students are also exposed to mass transport mechanisms not usually encountered in undergraduate courses, such as pressure diffusion, forced diffusion (electrophoresis), and the Soret effect. In a typical problem at this point, students are asked to analyze a Clusius-Dickel column (a separations device which relies on the Soret effect), where they are required to determine what assumptions are necessary to obtain a solution.

The last formal topic discussed in the course involves the unsteady one- and two-dimensional diffusion of a trace pollutant, focusing on problems such as the steady or unsteady discharge from a waste pipe into a stream. The similarity between pollutant concentration distributions resulting from the unsteady convective diffusion equation and a probability distribution arising from stochastic differential equations is emphasized. The final two lectures are devoted to research interests: one lecture by a professor whose research is in the area of energy or mass transport, and one lecture by a student in the class working in the same area who by this time is getting ready for the first year comprehensive oral examination. These last lectures give the students some feel for the utility of the topics and techniques discussed during the semester in the solution of current graduate research problems.

In conclusion, this course sequence is designed to meet the needs of students from diverse backgrounds who enter our graduate program. Students are first introduced to the governing physics without undue emphasis on mathematical techniques. As their level of understanding increases and their problem solving approach becomes better refined, more sophisticated techniques are introduced. When students have com-

Continued on page 218.

A course in . . .

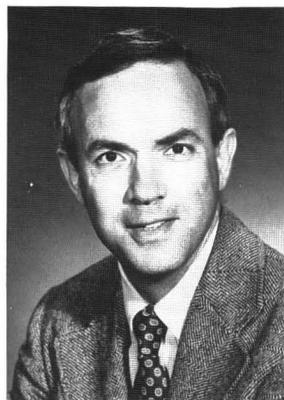
NONLINEAR SYSTEMS

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DURING THE PAST three years we have provided our graduate students with a third, optional, course on the mathematics of nonlinear systems. The course follows two required courses that formalize the structures of linear, or vector, spaces and nonlinear metric spaces leading to the solution of partial differential equations. These two courses have been described by Lauffenburger, *et al* [1].

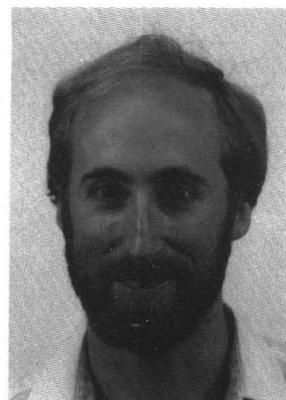
The nonlinear math course provides an opportunity for the students to examine the complex solution spaces that chemical engineers encounter in modeling many chemical processes, especially those involving reaction and diffusion, autocatalytic reactions, phase equilibrium in the critical region, and multistaged operations. Some of the simplest exothermic reactions in CSTRs with heat transfer exhibit branches in their solution diagrams that contain limit and bifurcation points, both steady-state and periodic, and trace out isolas as parameters are varied. For such systems, solution diagrams are calculated to show the importance of characterizing the singular points and expressing their normal forms and universal unfoldings so as to determine the number of steady state solutions in their vicinity. Examples are selected to demonstrate steady-state foci that bifurcate to time-periodic limit cycles which, in turn, undergo secondary bifurcations that lead to chaotic behavior, and even intermittent interchanges between periodic and chaotic modes of operation. Experimental observations of these phenomena are reviewed to drive home the importance of developing models that have corresponding solutions. In many cases, the models have complex solution diagrams that *don't* correspond to the experimental mea-

The nonlinear math course provides an opportunity for the students to examine the complex solution spaces that chemical engineers encounter in modeling many chemical processes . . .



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Lyle Ungar joined the faculty at Penn in 1984 as assistant professor, having received his BS degree at Stanford and his PhD at MIT. His research interests include application of perturbation methods, bifurcation theory, and finite element analysis to transport problems in continuum physics, crystal growth and rapid solidification materials processing. He is also applying artificial intelligence programming techniques to process control problems. (R)



surements and which emphasize the importance of locating the solution that most closely matches the data.

Nonlinear phenomena, such as the formation of spatial and temporal patterns and chaotic behavior, arise naturally in many systems with fluid flow or chemical reaction. Combustion, natural and forced convection, biological systems with competing species, and catalytic reactions can all require nonlinear analysis. Nonlinearities can also be generated in the design of complex processes, such as those integrated to achieve a high thermodynamic efficiency, and can introduce oscillatory and chaotic regimes that can present pitfalls and obstacles to easy operation and control. The design of these processes usually begins with the analysis of simple structures using approximate models. Gradually, as the synthesis tree is

pruned, more complex models can be justified to represent the real phenomena more accurately. However, the more complex models usually have a richer solution space and the number, type (steady, periodic, or chaotic) and stability of the solutions varies with the specifications and the parameters of the model. In design calculations, as in all mathematical modeling, the student must learn to beware of algorithms that converge to solutions that are not physically correct. The seriousness of this problem in the design stage, when experimental data are not available, is emphasized. Of course, when the solutions are observed experimentally, it is important to recognize the possible existence of multiple solutions and to design control systems to achieve the desired performance. This permits focusing on designs that have few regimes of operation; that is, less complex solution diagrams.

EVOLUTION OF THE COURSE

The initial version of the course concentrated on the general aspects of bifurcation and singularity theories with examples of many applications that arise in chemical processing. Emphasis was placed on the use of analytical perturbation methods to analyze nonlinear systems. A variety of techniques were covered for describing steady and oscillatory bifurcations and how they change as parameters are altered [18]. No computations were carried out, so complete solution diagrams were obtained only for very simple problems. Continuum problems such as natural convection were studied at the end of the course, but only the onset of instability could be covered in the homework exercises. This approach closely parallels that of Iooss and Joseph [3] in their text, *Elementary Stability and Bifurcation Theory*, which was the principal reference in that initial offering. That text has several limitations, the most severe being the lack of physical examples and the lack of coverage of chaotic phenomena. A mixture of papers from the math, physics and engineering literatures was therefore used as supplements.

In the most recent version of the course (Spring, 1987), emphasis was shifted more toward the process models and the methods of computing the singular points and the branches that connect them in solution diagrams. This was facilitated by improvements in available texts and software. Kubicek and Marek's [2] text, *Computational Methods in Bifurcation Theory and Dissipative Structures*, provides a unified approach to the analysis of solution diagrams. Several process models are introduced in Chapter 1. Then, as

In the most recent version of the course, emphasis was shifted more toward the process models and the methods of computing the singular points and the branches that connect them in solution diagrams.

the singular and bifurcation points are defined, examples are illustrated in the solution diagrams for these process models. General methods are presented to compute the singular and bifurcation points and the branches that connect them. These are very helpful, but unfortunately many of the definitions are stated briefly and the figures and tables in which the results are presented are explained insufficiently. Many questions arise which can only be answered by computational experiments. To accomplish this, we initially introduced our own program for the continuation of steady-state solutions [8] and placed some emphasis on the logic that enables it to traverse turning-points effectively. Midway through the semester we obtained a copy of the AUTO program [29], and this added immeasurably to the course. AUTO enabled us to perform computational experiments with ease and to answer many questions, especially those concerning branches of periodic solutions. These will be considered in the next section, in which the syllabus for the course is presented and the role of AUTO is described.

COURSE CONTENTS AND PHILOSOPHY

A central aspect of the course as it has evolved is the integration of analytical and numerical techniques and their application to physical problems. Analytical techniques and theorems provide a general framework for understanding how and when stability can change and new solution branches can arise. Numerical calculations provide complete solution diagrams for specific physical problems. Interpreting these solution diagrams in the contexts of both singularity theory and the physical problem from which they arise gives students a better understanding of nonlinear phenomena.

The core of the course concentrates on the methods of analyzing what happens at and near different steady and time-periodic bifurcations (see Table 1 for a list of topics covered). To calculate bifurcations of nontrivial solutions, one must generally turn to the computer. Hence, major effort was devoted to numerical techniques. All numerical techniques essentially grow out of analytical perturbation techniques. When using Newton's method, the linearized equations are present and so one can, for example, monitor the determinant to find steady bifurcations and check for changes in stability without calculating the eigen-

values. The implicit function theorem guarantees that stability can only change when the determinant vanishes; arc-length continuation around limit points [5] naturally grows out of the classification of limit points and steady bifurcation points, and Poincaré maps provide the basis for calculating time-periodic solutions. The latter can be difficult to compute, especially when the branches of limit cycles are unstable. Hence, the Newton-Fox procedure for locating a point on the limit cycles is described, following the approach of Aluko and Chang [27]. Stability analysis of the Monodromy matrix, according to the Floquet Theory, and the methods of continuation to locate secondary bifurcations lead naturally to studies of the transitions to chaos.

We have tried to integrate smoothly the three different aspects of the course: analytical methods, numerical methods, and physical insight. The general theory is illustrated throughout with examples, and relevant computational techniques such as homotopy methods are covered as they are used.

For example, we have used the Belousov-Zhabotinskii reaction system as an example of steady and time-dependent bifurcations and of chaotic behavior. This relatively simple set of reactions has been

observed to produce a bewildering variety of spatial and temporal patterns, and has been widely studied as a simple prototype for many reaction-diffusion systems. These have been summarized nicely in a review article by Epstein [41] that illustrates the regimes of periodic behavior with beautiful color photographs of the oscillations in a stirred beaker and in a Petri dish with diffusion effects. In our coverage, the initial kinetic model of Field and Noyes [33] was presented and mass balances were derived for the three principal intermediates, HBrO_2 , Br^- and Ce^{4+} :

$$\frac{dy_1}{dt} = 77.27 (y_2 - y_1 y_2 + y_1 - k y_1^2)$$

$$\frac{dy_2}{dt} = (-y_2 - y_1 y_2 + y_3) / 77.27$$

$$\frac{dy_3}{dt} = 0.161 (y_1 - y_3)$$

whose dimensionless concentrations are y_1 , y_2 , and y_3 , respectively. For this mechanism, which assumes the autocatalytic formation of HBrO_2 , the rate constant k is a key parameter. Steady-state continuation calculations show that as k is decreased, the L_2 -norm of y increases, as illustrated in Figure 1. At $k = 0.02394$, a Hopf bifurcation point is encountered. The steady-state branch becomes unstable and a new branch is born. Early in the course, the students computed Figure 1 using our continuation program and located the Hopf bifurcation point by computing the eigenvalues of the Jacobian along the steady-state

TABLE 1
Course Topics

BACKGROUND

- Implicit function theorem
- Stability theory

STEADY BIFURCATIONS

- Single and multiple limit points
- Continuation methods
- Liapunov-Schmidt reduction
- Effect of a second parameter
 - Perturbed and "broken" bifurcations
- Singularity theory
 - Normal forms, unfoldings
 - Representation of energy for conservative systems

TIME DEPENDENT BIFURCATIONS

- Floquet theory
- Hopf bifurcations
- Integration of stiff ODEs
- Secondary bifurcations

CHAOTIC BEHAVIOR

- Transitions to chaos
 - Period doubling
 - Incommensurate frequencies
 - Intermittency
- Characterization of chaos
 - Power spectra
 - Poincaré sections and maps
 - Liapunov exponents

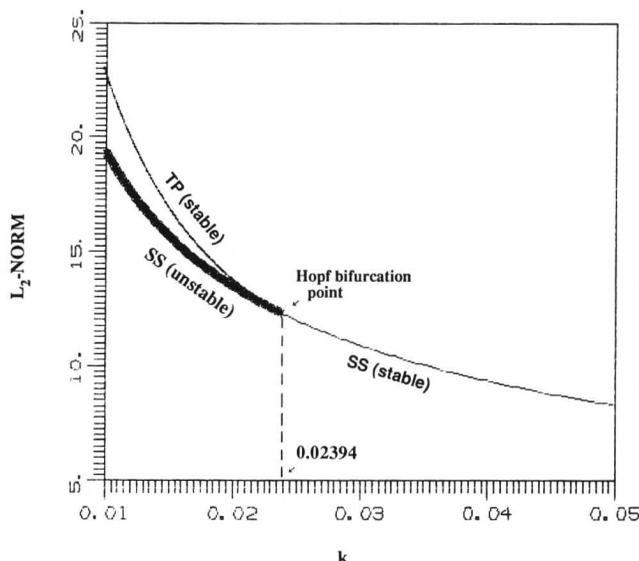


FIGURE 1. Steady and time-periodic branches for the Belousov reaction system (TP—time periodic, SS—steady-state).

branch. Then, with the LSODE program, they plotted the limit cycles in the time-domain (see Figure 2), and showed the decrease in the frequency of oscillation as k decreases. Finally, the AUTO program performed these calculations with much less preparation and traced the periodic branch in more detail, showing the variation of the frequency with k . This analysis led naturally to several papers that show how chaotic behavior arises in CSTRs and introduces alterations in the model to track these strange attractors [38, 39, 40]. As expected, computational experiments by the students with the AUTO program were unable to track the strange attractors, but success was achieved with LSODE. These results are displayed in the phase-plane of Figure 3, which closely resembles the results illustrated by Epstein and others.

The AUTO program was a great aid in enabling students to calculate solution structures and to get a feel for how nonlinear systems behave. AUTO is a collection of FORTRAN routines whose primary pur-

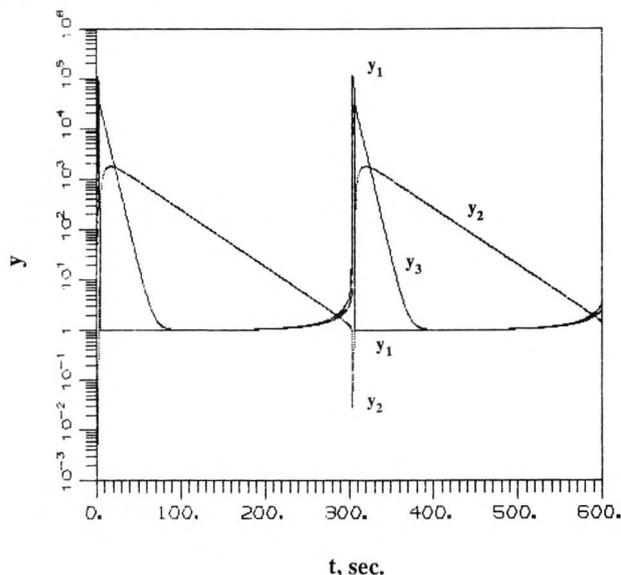


FIGURE 2. Dynamic simulation of Belousov reaction system with $k=8.375 \times 10^{-6}$.

pose is to compute the branches of stable or unstable periodic solutions of systems of ODEs that are functions of a free (bifurcation) parameter. AUTO also determines the branches of steady-state solutions, locates limit and real bifurcation points along solution branches, and can switch branches at these points. It can also locate limit points and curves of Hopf bifurcation points using two-parameter, continuation methods. A tape containing the AUTO routines was installed on our VAX computer, under the VMS operating system, in less than two hours. Of special note is that AUTO is currently limited to small ODE

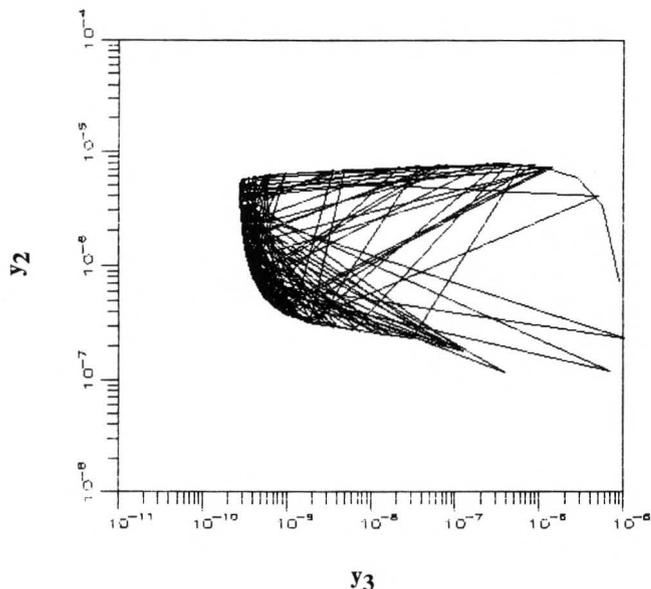


FIGURE 3. Phase-plane for Belousov reaction system. Turner model with $\tau=0.2962$.

systems (up to twelve state variables). Computations of steady branches normally proceed very rapidly, whereas time-periodic branches can be slow to compute, especially when they are unstable.

At the end of the course, the students studied articles on either analytical or numerical techniques or on specific systems that exhibit interesting nonlinear behavior and made presentations to the class. A list of project areas and references is given in Table 2. In the initial version of the course emphasis was placed on classic papers describing the effect of container shape on the onset of natural convection, pattern formation due to competing biological species (predator-prey systems with similarities to the Belousov-Zhabotinskii system) and different transitions to turbulence in forced convection. Several mechanical engineering students enrolled in the course studied bifurcation-based descriptions of buckling. In 1987, the papers focused on chemical processes that exhibit complex solution diagrams, usually with transitions to chaos. Several of these papers present the latest results of studies of systems that naturally exhibit chaotic behavior or become chaotic under the influence of forced oscillations.

CONCLUSIONS

Nonlinear phenomena are ubiquitous. They have received little attention largely because the required mathematics is less well-developed and harder to comprehend than for linear systems. Bifurcation and singularity theory provide a framework for classifying and understanding nonlinear phenomena. They follow

very easily from a linear operator approach and provide a dramatic demonstration of the constructive use of Fredholm's alternative. This has enabled us to successfully touch on bifurcation theory in the last days of the prior required portion of our graduate math sequence. When bifurcation techniques are implemented in a computer package such as AUTO, they also provide a means of mapping out solution structures. Students can obtain an intuitive understanding of nonlinear phenomena by examining the solutions to physical problems. With the right software, they can also generate these solutions themselves and prepare an array of two- and three-dimensional drawings that permit more thorough analysis and visualization than is possible with the few drawings that typically accompany technical articles and books.

ACKNOWLEDGMENTS

The assistance of Soemantri Widagdo, Stevens Institute of Technology, in the preparation of the class notes and homework problems, and in the installation of the AUTO program, is very much appreciated. Prof. Robert A. Brown, M.I.T., taught Lyle Ungar his first course in nonlinear systems in chemical engineering and strongly influenced his view of the field.

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TABLE 2
Sample of Articles Reviewed

EARLIER ARTICLES	
AUTHOR	TITLE (Reference No.)
Hall, Walton	Benard Convection in a Finite Box: Secondary and Imperfect bifurcations (42)
Keener	Oscillatory Coexistence in the Chemostat: A Codimension Two Unfolding (43)
Segel	Mathematical Models in Molecular and Cellular Biology (44)
Eckmann	Roads to Turbulence in Dissipative Dynamical Systems (55)
Thompson, Hunt	A General Theory of Elastic Stability (45)
Triantafyllidis, Tvergaard	On the Development of Shear Bands in Pure Bending (46)
FOCUS ON CHAOTIC BEHAVIOR—1987	
Kahlert, Rossler, Varma	Chaos in a Continuous Stirred Tank Reactor with Two Consecutive First-order Reactions: One Exo-, One Endothermic (50)
Mankin, Hudson	Oscillatory and Chaotic Behavior of a Forced Exothermic Chemical Reaction (51)
Mankin, Hudson	The Dynamics of Coupled Nonisothermal Continuous Stirred Tank Reactors (52)
Kim, Hlavacek	On the Detailed Dynamics of Coupled Continuous Stirred Tank Reactors (32)
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A course in . . .

POLYMERIZATION REACTOR ENGINEERING

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MICHIGAN TECHNOLOGICAL University, together with the Michigan Molecular Institute (MMI) and Central Michigan University, has formed the Michigan Polymer Consortium to provide graduate degree programs and collaborative research in polymer science and technology. Michigan Tech brings to the consortium the particular strengths of a combined Department of Chemistry and Chemical Engineering, conducive to interdisciplinary research, and an extensive research program in polymer composite materials.

In support of the polymer research program the department of chemistry and chemical engineering at Michigan Tech has structured a series of elective courses, open to graduate students and qualified seniors, grouped in four blocks (see Table 1). Although the blocks stand by themselves and can be taken in any order, students are advised to traverse the sequence in the direction shown.



J. M. Skaates received his BSc (1957) at Case Institute of Technology and his MS (1958) and PhD (1961) at Ohio State University. He worked at California Research Corporation for three years before joining the faculty at Michigan Tech. His teaching duties have included undergraduate and graduate courses in thermodynamics and kinetics, an undergraduate course in process control, and graduate courses in catalysis and in process optimization. He has been involved in research in catalysis, biomass pyrolysis, and wet oxidation.

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TABLE 1
Sequence of Polymer Courses

Polymer Chemistry	→	Polymerization Reactor Design	→	Polymer Forming Operations	→	Composite Materials
Polymer synthesis Polymer properties		Design and operation of polymerization reactors		Rheology Extrusion Molding etc.		Compounding and mechanical properties of composites
(five courses)		CM490		(three courses)		(courses in materials science and solid mechanics)

The polymerization reactor engineering course (CM 490) has as its focus the design and operation of industrial polymerization reactors to achieve a desired degree of polymerization and molecular weight distribution. Topics covered in the ten-week course are shown in Table 2. For the benefit of students who have not taken the polymer chemistry courses, the mechanisms and kinetics of polymerization reactions

TABLE 2
Topics Covered in CM490

- Kinetics of condensation polymerization
- Design of condensation polymerization reactors
- Design of agitated thin-film evaporators
- Kinetics of addition polymerization
- Mechanism of free-radical addition polymerization
- Autoacceleration
- Predicting molecular weight distribution in addition polymerization
 - Generating function method
 - Moment generating function
 - Z transform methods
 - The continuous variable technique
- Gel permeation chromatography
- Copolymerization kinetics
- Types of polymerization reactors
- Control and stability of addition polymerization reactors
- Optimization of polymerization reactors
- Flowsheets for the production of polystyrene
- Flowsheets for the production of polyethylene

are treated first. From the many available textbooks emphasizing different aspects of polymer science, the text by Rudin [1] was chosen because of its outstanding treatment of polymerization kinetics.

Polymerization reactor design and operation are taught with the aid of a series of literature articles (Table 3). These were selected to illustrate the development of experimental technique and sophistication of modeling during the past two decades. These papers are assigned, in the order shown, at the rate of two or three per week. Students must answer a series of written questions on each paper and these homework assignments constitute 20% of the course grade. Discussion of the papers, led by student volunteers, is carried out at the weekly recitation session.

TABLE 3
Assigned Outside Readings

1. Duerksen, J. H., A. F. Hamielec, and J. W. Hodgins, "Polymer Reactors and Molecular Weight Distribution: Part I. Free Radical Polymerization in a Continuous Stirred Tank Reactor," *AICHE J* 13, 1081 (1967)
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In support of the polymer research program, the department of chemistry and chemical engineering at Michigan Tech has structured a series of elective courses open to graduate students and qualified seniors, grouped in four blocks.

The study of reactor modeling centers largely around the work of the two leading research groups in the field—those of W. Harmon Ray at the University of Wisconsin-Madison, and of A. Hamielec at McMaster University.

Two weeks of the course are devoted to the difficult problem of predicting the molecular weight distribution in a free-radical addition polymerization. The topic begins with a discussion of the possibility of direct solution of all the rate equations, as exemplified by the monumental paper of Liu and Amundson [2]. Attention is then directed to mathematical techniques for compressing these equations using generating functions or the z transform. It is emphasized that limiting assumptions are often required to make these techniques computationally feasible. Finally, the continuous variable technique, pioneered by Zeman and Amundson [3], is presented as the logical successor to the other methods. A twenty-page handout tracing the important mathematical ideas in Zeman's thesis is given to the students. It is shown that Zeman's idea of replacing the discrete variables by continuous variables has been successfully applied to other fields (size reduction, crystallization, aerosol physics) where detailed population balances are required to understand observed rate behavior.

Industrial practice in polymerization reactor design is introduced with the excellent review articles of Albright and Bild, and Gerrens. These are supplemented by a series of overhead transparencies showing polymerization reactors in industrial installations. Auxiliary equipment (agitated thin film evaporators, motionless mixers, vented extruders) used to complete the polymerization and remove unreacted monomer, is also described. The course closes with the study of flowsheets for two important families of polymers (polystyrene, polyethylene), starting with monomer synthesis and purification, and going to the various grades of finished polymer.

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ADVANCED ENGINEERING FIBERS

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A NEW GENERATION of composite materials is revolutionizing today's aircraft and automotive industries [1]. In applications ranging from the globe-circling Voyager aircraft to truck drive shafts, composites are demonstrating properties which are superior to traditional materials. In aircraft applications where weight, strength, and stiffness are critical, many structural components are now made using graphite/epoxy composites. Looking ahead, approximately half of the structural weight of the Air Force's advanced tactical fighter will be composite materials. Composites of glass and carbon fibers surrounded by epoxy and polyester are being increasingly utilized in

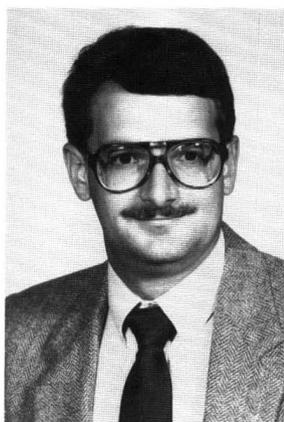
automobile structure applications. Although U.S. auto production in 1986 fell 3.7% from the 1985 level, composites shipments to the industry rose 3.0%, reaching 585 million pounds [2]. The high-temperature strength and stability of fiber reinforced ceramics offer the promise of more fuel efficient engines in tomorrow's automobiles. In the future, plastics, metals and ceramics reinforced with graphite, glass, aramid, and other fibers will replace much of the metal in aircraft and automobile structures.

In a composite, a structure of fibers provides strength and stiffness, and these fibers are held together by a matrix material. The result is that the properties of a composite material can be exactly tailored to fit the structure. For example, if one end of the structure is under a higher load, more fibers (or higher strength fibers) can be added to that end of the composite structural member.

A composite for use at moderate temperatures normally consists of high-strength carbon or polymeric fibers encased in a plastic matrix. Higher temperature applications may require either carbon or ceramic fibers to be embedded in a metal, ceramic, or carbon matrix. The fiber and matrix are carefully selected to provide the best composite properties for the particular application.

CHEMICAL ENGINEERING'S ROLE

Composite materials represent a major growth market for the chemical industry. In the future, chemical companies, rather than metal producers, will be the major raw material suppliers for the automotive and aircraft industries. Even commercial building and highway construction may utilize significant amounts of composite materials. Since the processing, development, and production of polymers has been an important part of chemical engineering for the last thirty years, research into the new high-strength fibers and matrix polymers is a natural extension. New research and development challenges in the fibers area include



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Michael G. Dunham, a PhD student in chemical engineering at Clemson University, received his BS degree from Clemson in 1980. Prior to returning to pursue an advanced degree, he served in a variety of technical and supervisory positions with the DuPont Company. In his research he is using mathematical modeling to study the stabilization and carbonization of carbon fibers. (R)

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Composite materials represent a major growth market for the chemical industry. In the future, chemical companies, rather than metal producers, will be the major raw material suppliers for the automotive and aircraft industries. Even commercial building and highway construction may utilize significant amounts of composite materials.

- Continually upgrading manufacturing processes for the fibers to improve properties and to reduce cost. Chemical engineers in industrial research have recently developed new processes to produce the precursors for many types of ceramic, carbon, and graphite fibers.
- A number of new high-performance fibers have been developed which are made from polymers as complex as polybenzimidazole and as simple as polyethylene. Chemical engineers must develop and design processes to produce these fibers on an economic commercial basis.

The polymer matrix materials are undergoing dramatic improvements. New polymers designed for improved toughness, temperature stability, and melt processability are being developed by a number of firms. Chemical engineers will be principally responsible for developing the processes used to produce and utilize these polymers.

Another major role for chemical engineers involves the fabrication of the composites themselves. Today, most advanced composites are made by manually laying up layers of matrix coated fibers or by winding the fibers into the desired shape. These expensive, labor-intensive processes limit end uses to very high value-in-use applications. The application of chemical engineering principles to the development of automated processes for these fibers, such as weaving, braiding, or the production of non-woven fabrics, will dramatically lower the cost of these materials. These automated processes require that future reinforcing fibers be less brittle and have improved finish coatings. Other processes such as thermoforming, injection molding, and pultrusion are also being explored by chemical engineers in order to automate composite manufacturing.

CLEMSON'S ADVANCED ENGINEERING FIBERS LABORATORY

To address these challenges, Clemson established the Advanced Engineered Fibers Laboratory in August of 1986. The laboratory's purpose is to provide national leadership and expertise in developing the processing equipment and advanced fibers necessary for the chemical, fiber, and textile industries to enter the composite materials market. Since the problems encountered are often too complex to be solved by a single academic program, the contribution of each of the fields involved in the laboratory is critical. Re-

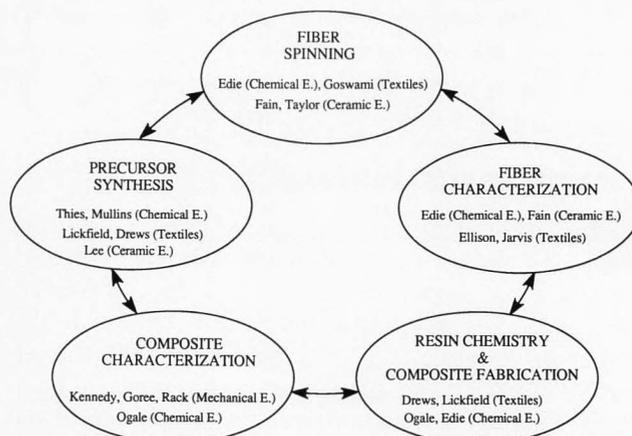


FIGURE 1. Advanced Engineering Fibers Laboratory areas of emphasis. Faculty from four academic departments participate in this unique research effort.

searchers in chemical engineering, textile science, polymer chemistry, mechanical engineering, and ceramic engineering all interact in laboratory research projects. The laboratory also offers technical and educational support to the fiber, textile, and composite materials industries.

Many universities study composite materials. However, this research effort has typically focused on the analysis, fabrication, and mechanical evaluation of the composite. Clemson's Advanced Engineering Fibers Laboratory is unique in that its efforts are directed toward the high performance fibers and matrix polymers so critical to composite materials. Research on these fibers, the matrix polymers, and their fabrication into textile structures using automated equipment is being coordinated by the laboratory. The laboratory conducts research in six primary emphasis areas

- The chemistry of engineering fiber precursors
- Fiber formation and processing
- Characterization of engineering fibers
- Fabrication of three-dimensional textile structures
- Composite material characterization
- Process economics and information transfer.

Figure 1 lists the faculty who are participating in

ongoing laboratory projects. It also indicates the interrelationship of the various research areas. For example, improvements in fiber formation processes require an understanding of precursor chemistry, an ability to characterize the resulting fibers, the fabrication and testing of the fibers in composites, and the assessment of the process economics. This gives the laboratory the unique ability to study high performance fibers from the chemical precursors through their application in composite structures.

CURRENT CHE RESEARCH PROJECTS

The Department of Chemical Engineering at Clemson has had an active and well-funded research program in polymer processing and fiber formation for years. The establishment of the Advanced Engineering Fibers Laboratory has augmented this effort and provided an increase in both internal and external funding for this important area of chemical and materials research. Numerous research projects are

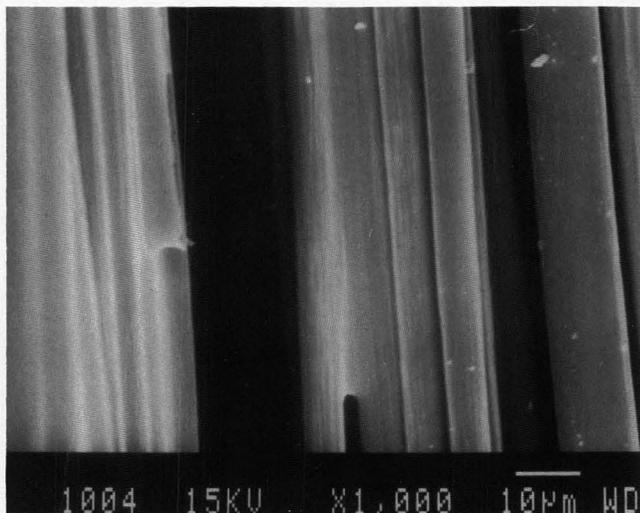


FIGURE 2. An electron microscope photograph of carbon fibers coated with LaRC thermoplastic polyimide. The electrical resistance of the carbon fiber is employed to melt the thermoplastic matrix material.

underway in the laboratory and the following are brief descriptions of several typical studies being carried out by chemical engineering graduate students.

Coating of Carbon Fibers with Thermoplastic Polymers. A novel process for coating carbon fibers with thermoplastic matrix materials is being developed. A polymer powder is applied to the carbon fiber and then melted by utilizing the electrical resistance of the carbon fiber itself [3]. An electrical poten-

For example, improvements in fiber formation processes require an understanding of precursor chemistry, an ability to characterize the resulting fibers, the fabrication and testing of the fibers in composites, and the assessment of the process economics.

tial is applied across a length of the fiber. This heats the fiber to a temperature higher than the melting point of the thermoplastic matrix and results in flow of the polymer throughout the fiber bundle. This technique is currently being used to apply new high-temperature matrix polymers such as LaRC thermoplastic polyimide (developed by NASA) and polyetheretherketone (developed by ICI) to carbon fibers. These tough matrix polymers have been specifically developed for aircraft applications. The polymer coating allows the brittle fibers to be readily woven or braided into a fabric which can be thermoformed into a composite material. Figure 2 shows an electron microscope photograph of a bundle of carbon fibers coated with LaRC thermoplastic polyimide using this technique.

Modeling of Heat and Mass Transfer in Carbon Fiber Manufacturing. Two of the most important steps in the manufacture of carbon fibers are stabilization and carbonization of the precursor fibers. Each of these steps involves high temperature and exothermic reactions which produce gaseous products. In order to better understand these processes and predict optimum conditions, an effort is underway to model these two process steps. The equations of heat and mass transfer are applied to each process step and solved simultaneously with equations describing the reaction kinetics. In order to accurately describe the reacting system, it is also necessary to determine several physical constants such as diffusivities and thermal conductivities as well as heat and mass transfer coefficients. Current work is directed toward understanding the reaction kinetics and measuring these constants and coefficients by a variety of experimental methods.

Non-Circular Carbon Fibers. Chemical and ceramic engineers at Clemson have developed a process for the production of non-circular carbon fibers by melt spinning mesophase pitch. The shape of the fibers has been found to dramatically affect the properties of the resulting composites [4, 5]. The goal of the current research is to improve the toughness of the fibers and resulting composites and to better understand the novel fracture mechanisms of non-circu-

lar fibers. Tougher fibers are needed if composite fabrication is to be automated to produce the inexpensive composite materials required for automotive applications. Figure 3 is an electron microscope photograph of a C-shaped fiber produced in this research.

Aging Characteristics of High Temperature Thermoplastic Composites. One of the most important trends in composites is toward tough, high temperature thermoplastics to replace the thermosetting polymers currently used as matrix materials. The proper design of composite materials which use these new thermoplastics will require more than the limited physical data presently available. Clemson chemical engineers are studying the effect of aging on composites of high temperature thermoplastics such as PEEK (polyetheretherketone) and carbon fibers through dynamic testing on a Rheometrics spectrometer. The loss modulus, a measure of the composite's ability to absorb energy, goes through a minimum at a certain frequency of the applied load. The effect of time, temperature, and composite processing history on this minimum are being studied. It is expected that this work will describe the high temperature limits of the material and provide important physical data to the composites industry.

THE LABORATORY'S ROLE IN EDUCATING CHEMICAL ENGINEERS

The laboratory offers no courses or degree programs. Instead, it complements the existing degree programs. The laboratory provides a mechanism for students and faculty to interact with other engineering and scientific disciplines. This is of increasing importance as chemical engineers enter new areas such as composite materials where polymer processing, fiber physics and mechanics, as well as chemical engineering principles, must be applied to solve process problems.

This interdisciplinary environment has long been used by companies for research, design, and process assistance. Normally, a variety of engineering and scientific fields are represented on industrial research and design teams. The laboratory exposes chemical engineers to a similar environment and permits the synergism which can be achieved as students and faculty with different backgrounds and skills work together to solve a problem.

The laboratory also provides a mechanism for sharing experimental facilities among four departments which are located in five buildings on the Clemson campus. This is important as equipment becomes more expensive and requires more expertise to oper-

ate. It provides chemical engineering students the opportunity to become familiar with processes as diverse as fiber spinning, composite characterization, and polymer spectroanalysis.

SUMMARY

Clemson's Advanced Engineering Fibers Laboratory provides a unique interdisciplinary environment for the study of high performance fibers and matrix polymers from their precursor chemicals to their final

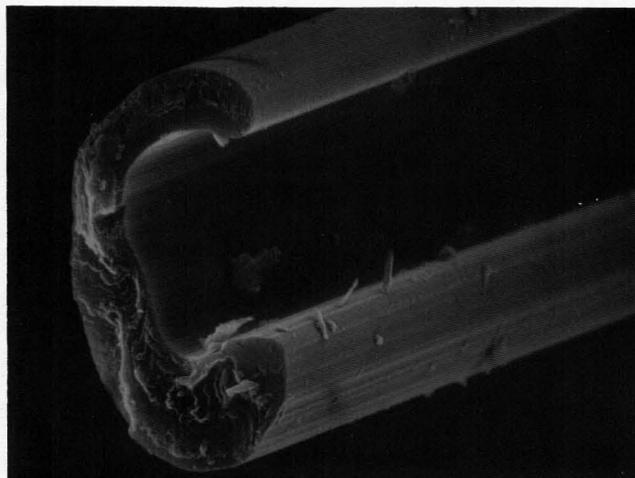


FIGURE 3. A C-shaped carbon fiber produced by melt spinning mesophase pitch. Non-circular fibers can offer improved physical properties and toughness.

application in composites. The interaction provided by the laboratory provides chemical engineers with an opportunity to explore other engineering and scientific approaches in solving problems. At the same time, the laboratory itself benefits from the traditional ability of chemical engineers to solve problems by utilizing ideas obtained from a number of sources.

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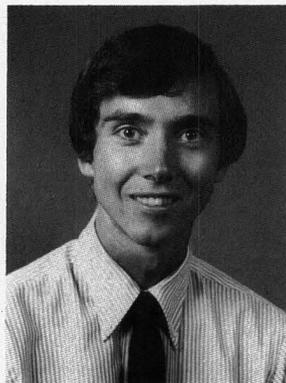
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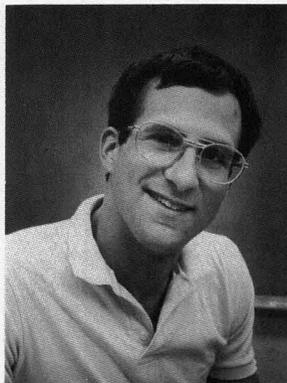
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THE SPACE SHUTTLE and the planned space station offer unique environments for chemical processing. The three basic advantages that space offers that are not generally available in earth-based systems are low temperature, high vacuum, and sustained periods of zero or microgravity. Ready access to low temperatures and high vacuum may allow for the development of processes requiring large structures in vacuum, long duration cryogenic cooling, or multiple vacuum to high pressure transitions. However, most of the unit operations that are being developed for materials processing in space are designed to take advantage of reduced gravity. The next few pages will present a brief review of some of the work currently under way in the development of microgravity processes. The material is largely based on a series of symposia held



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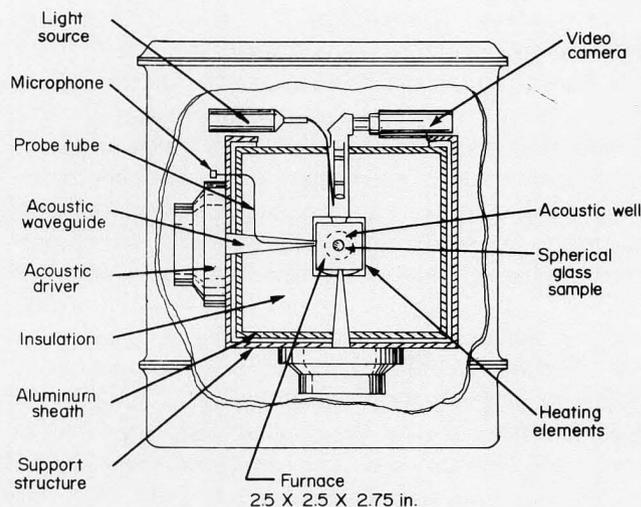


FIGURE 1. Containerless furnace based on acoustical levitation (ref. 6).

at AIChE meetings since 1985 [1, 2] and a group of NASA publications [3-5]. Our goal in performing this review is twofold. First, we seek to highlight some of the opportunities for materials processing in space, and second, we want to emphasize the contributions that chemical engineers can make in this emerging set of technologies.

UNIT OPERATIONS IN MICROGRAVITY

A spacecraft orbiting the earth at an altitude of approximately 190 miles is only 6% farther from the center of mass of the earth mass than an object on the earth's surface. Thus, the gravitational force experienced by the spacecraft is only 13% less than the gravitational force at the earth's surface. However, because the spacecraft and all of the objects in it are in free fall, there is no gravitation acceleration of the objects in the spacecraft relative to the spacecraft. The objects are in an approximately weightless, or zero gravity, environment in the frame of reference of the moving spacecraft. But even in the spacecraft's frame of reference the gravitational force is not precisely zero. There are two types of gravitational force experienced in the spacecraft. The largest forces are induced by small vibrations in the ship (*g*-jitter), which can cause a gravitational force of order 10^{-3} *g*.

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G-jitter is roughly random and averages out to a zero net force. A constant force of order 10^{-6} g is caused by gravitation gradients. The gravitation force in low earth orbit changes at a rate of 10^{-7} g per meter as an object moves away from the center of mass of the spacecraft. In a spacecraft with a dimension of 10 m, a force of order 10^{-6} g can be imposed.

Reduced gravity allows two classes of unit operations to be used in space processing that are not generally available in a one-g environment. The first type of unit operation uses various means of levitation to achieve containerless processing, and the second type is based on the absence of buoyant and sedimentation forces.

CONTAINERLESS PROCESSING

In a microgravity environment objects levitate and will assume a conformation that minimizes interfacial energy. Thus, it is possible to contain liquids and to process solids without exposing the materials to vessel walls. The concept of levitation is not new, nor is it confined to microgravity environments. Indeed, Robert Millikan first measured the charge of an electron by levitating a charged oil drop in an electromagnetic field. However, the masses that can be levitated in an earth-based experiment are limited, and the levitating force can cause significant heating and distortion of the material. In a microgravity environment, levitating forces are imposed primarily to counter the small gravitational forces discussed earlier or to adjust an object's position. Much larger masses can be levitated in space than on earth, and heating effects are not as important.

Electrostatic suspension, acoustic standing waves, photon beams, gas or vapor stream momentum, and magnetic induction have all been proposed as levitation mechanisms for containerless processing in space. The containerless processing apparatus that has seen the most extensive use on the space shuttle is acoustical levitation. If the object to be suspended can be exposed to a gaseous environment, acoustical drivers (loudspeakers) can be used to control the position of the object. In a typical configuration, three mutually perpendicular acoustical drivers are used to produce a 3-dimensional standing acoustical wave in a roughly cubical box (Figure 1) [6]. An energy well is created at a position dependent on the wavelength generated by the acoustical drivers. Containerless systems that

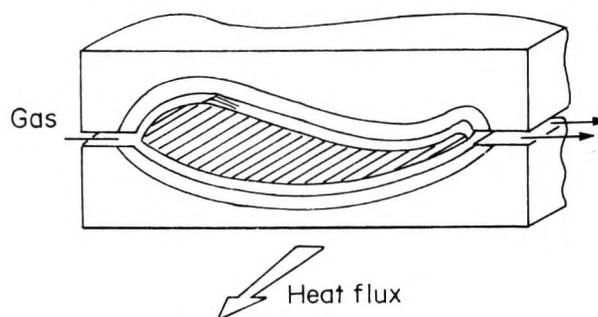


FIGURE 2. Conceptual configuration of a containerless process for casting unusual shapes (ref. 7).

can impose a desired shape on a deformable material are shown conceptually in Figure 2 [7]. These devices use gas momentum to suspend objects and could be useful in casting parts of arbitrary shape.

The ability to levitate relatively large masses in microgravity has resulted in a number of applications. The primary applications have been in suppressing heterogeneous nucleation during crystal formation and in the production of new glasses and unusual alloys. Crystallization and the production of new glasses will be considered briefly in this review because they represent two quite different examples of containerless processing (*i.e.*, semi-containerless and truly containerless).

When a glass forming melt is suspended in a levitation device, heterogeneous nucleation is suppressed. The outgrowth of this phenomena is the ability to extend the compositional limits of glasses, making possible entirely new materials. One such class of materials is fluoride glasses, which have great promise as infrared optical components [8, 9]. A second possibility for generating unique materials by containerless processing in microgravity is the production of millimeter size glass shells with walls of thin, uniform thickness [10]. Many other applications are envisioned through the use of controlled gradient furnaces coupled with levitation devices.

These processes can be regarded as truly containerless. However, they are forced to operate in a batch mode. Semi-containerless unit operations can be operated continuously. One such process involves the crystallization of materials important in electronic devices and utilizes Czochralski growth (Figure 3) [5]. In this unit operation, a seed crystal is lowered onto the free surface of a melt. As the seed is withdrawn, the melt

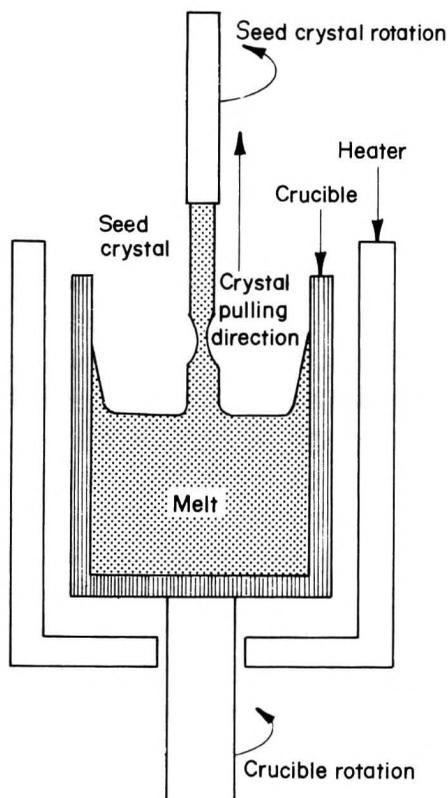


FIGURE 3. Semicontainerless process for crystal growth.

adhering to it solidifies. This unit operation can be performed in one g. However, less defects are present in crystals produced in microgravity than in similar crystals produced on earth. The defects in one g are due, in part, to convective stirring caused by the heat of crystallization. In microgravity, buoyant driven convective motion is significantly reduced. Problems associated with this unit operation in microgravity are contamination by impurities derived from the crucible and the difficulties associated with maintaining a flat melt surface in microgravity.

A second semi-containerless unit operation is float zone refining. Figure 4 shows a typical float zone crystallization configuration. The feed crystal, containing imperfections, is melted and then slowly recrystallized. The purpose of the float zone is to insure uniform dispersal of dopants, reducing imperfections. The float zone (melt) is suspended by interfacial tension between the feed material and the crystal. In microgravity, much larger float zones are possible than at one g and concentration inhomogeneities due to convective motion and growth spurts are minimized [11]. A new approach to float zone crystallization is shown in Figure 5. In this system [12] the crystallizing material is isolated by the float zones, and a seed crystal is not required.

UNIT OPERATIONS BASED ON REDUCED SEDIMENTATION AND BUOYANCY IN MICROGRAVITY

Sedimentation and buoyancy effects are greatly subdued in microgravity relative to one-g operation. This can be extremely advantageous in electrophoretic separations, making metal foams, and in the production of unique alloys. However, the absence of buoyancy makes some unit operations that are easily done on earth much more difficult. For example, removing bubbles from glasses [13], obtaining reasonable mass transfer rates in aerobic reactors, and even operating a distillation column become difficult. For the moment let's consider only the advantages of space processing by focusing on electrophoresis and the creation of new materials.

Electrophoretic separations are frequently used to isolate biological molecules and cells. The separation is based on the net charge obtained on molecules or cells when they are placed in a buffer solution. The ions in the buffer associate with the species to be separated, providing a net charge. An applied electric field causes an ionic current to flow and generates a force on the charged species. The charged molecule or cell moves with a velocity that balances the electrical force with viscous drag. Because the charge associated with particular molecules and cells are highly structure-dependent, different species will migrate at different rates, allowing them to be separated as shown in Figure 6. Like most of the unit operations discussed in this brief review, electrophoretic separations are not

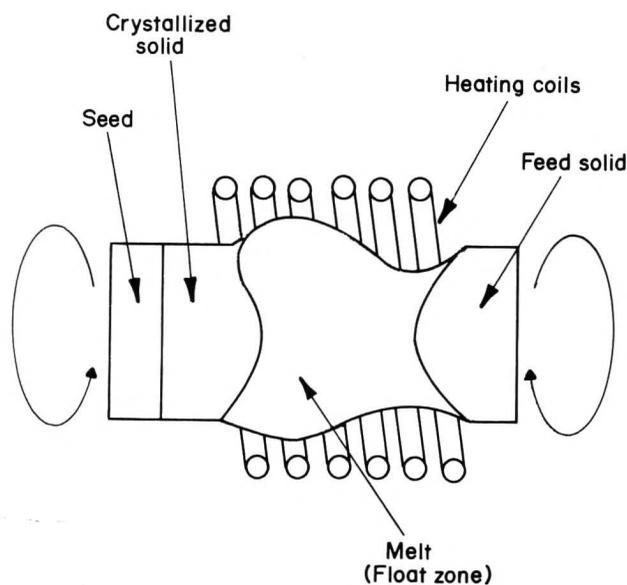


FIGURE 4. Float zone crystallization: a semicontainerless unit operation.

confined to microgravity environments. However, in one-g the resistive heat generated by the ionic current causes convective flow fields that can significantly degrade the quality of an electrophoretic separation. The sedimentation of cells can also degrade the separation. Since microgravity can eliminate some of these problems, electrophoretic separations in space have been actively investigated since the flights of Apollo 14 and Apollo 16. Most recently, McDonnell Douglas Astronautics Corporation has used continuous flow electrophoresis on board the space shuttle to separate biological model materials [14]. Chemical engineers are actively involved in modeling this complex phenomenon [15, 16].

Another type of unit operation which takes advan-

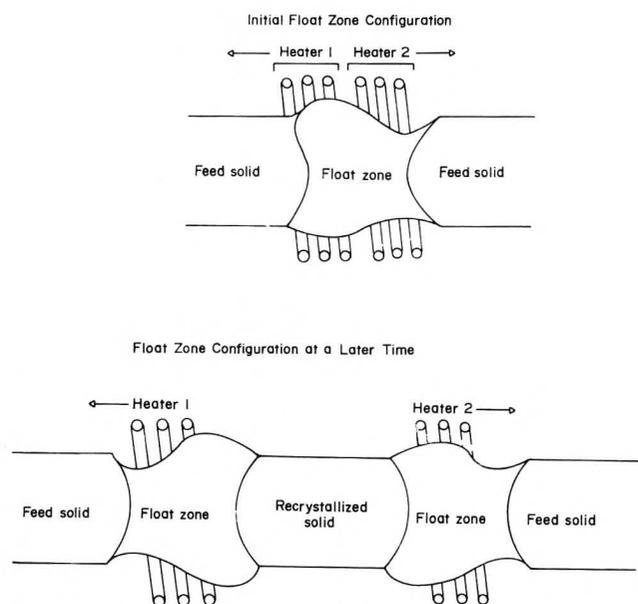


FIGURE 5. A new approach to float zone crystallization.

tage of reduced sedimentation is exemplified by a proposed method for growing zeolites in microgravity [17]. When zeolites are formed in solution, their size is controlled by nucleation rates and the rate at which crystals sediment out of solution. In microgravity, the crystals can grow to a much larger size before they sediment, and nucleation rates may be reduced. This process is representative of a large class of processes that rely on solutions remaining homogeneous in microgravity.

To this point, we have considered only unit operations that exploit microgravity. While microgravity can be beneficial, it can also cause difficulties in performing operations that are quite easily done at one-g. As an example, consider some of the unit operations required for optimizing the spacecraft ecosystem. In

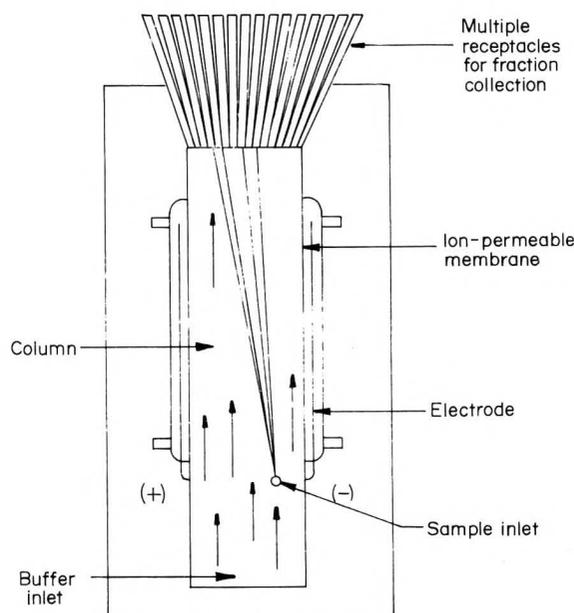


FIGURE 6. Electrophoretic separation.

a long spaceflight there is strong motivation to use biological reactors to convert CO_2 to O_2 in order to reduce the amount of oxygen required for life support. In one-g reasonable rates of mass transfer can be obtained in biological reactors by bubbling gases through the reactor. In microgravity, bubbles do not rise due to buoyancy. However, it may be possible to immobilize cells on microcarriers and then obtain reasonable rates of mass transfer through agitation. But, agitation may result in cell damage. This unit operation is still under active development by chemical engineers collaborating with NASA [18].

CONCLUSION

This paper has enthusiastically reviewed a few of the many opportunities available for materials processing in space. This enthusiasm must be tempered, however, by the enormous costs associated with transporting material into space. These costs have been estimated to be several thousand dollars per pound. With these transportation costs, the value added by microgravity processing must approach that of turning lead into gold. While the value of some pharmaceuticals may justify manufacturing processes based on microgravity alchemy, in general the costs of microgravity processes must be justified by our improved understanding of the role of gravity in earth-based processes. So, although no great economic incentive exists to build manufacturing processes in space, unit operations in microgravity will continue to be developed. Opportunities exist for chemical en-

Continued on page 218

A program on . . .

CHEMICAL PROCESS MODELING AND CONTROL

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WHEN DECIDING TO go on to graduate school, the prospective student must face two crucial questions: What to study, and Where? Certainly, anyone's answer to these questions will reflect a natural self-interest, but this article will describe some features of studying process modeling and control at Lehigh University that are exciting to us.

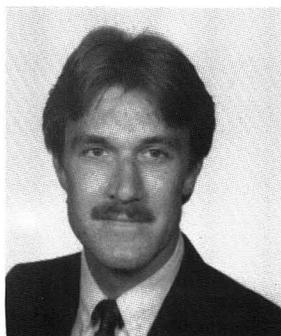
The combination of substantial economic incentives and profound intellectual challenges has motivated increasing emphasis on process control within the chemical process industries and chemical engineering academia. As the chemical process industry matures, business success depends more on optimizing the performance of existing or novel process technology and less on manufacturing new products with little attention to costs. No longer do overdesign and relaxed operating criteria make life easy. Even in biotechnology, specialty chemicals, and other frontier areas toward which the chemical process industry is migrating, profitable manufacturing requires the ability to understand and regulate dynamic processes. At the intellectual level, process control engineers are addressing issues that were once simply mathematical abstractions, but that now translate to real-world concerns like energy efficiency, manufacturing flexibility, product quality, safety, environmental protection, and computer-integrated manufacturing. For today's and tomorrow's chemical engineer, therefore, process modeling and control skills are important, regardless of his or her specific technical area of employment or research interest.

To meet this challenge to chemical engineering education, Lehigh University initiated the Chemical Process Modeling and Control Center (PMC) in 1984. PMC is an industry/academia consortium dedicated to the education of graduate students for advanced research in process modeling and control. Currently, PMC is sponsored by twelve companies (both U.S. and European), by the National Science Foundation, and by the Commonwealth of Pennsylvania. Its annual

operating budget is in excess of \$400K. Christos Georgakis and William Luyben are the center's founders and its co-directors.

As a result of the industry/academia partnership in PMC, the research work carried out by the students is neither all theoretical nor all applied, but is a delicate balance of both. PMC students can be confident that their research topic is novel and challenging in the context of the scientific literature and that it is relevant to professionals working at the highest technical levels of industry. The vigorous intermixing of the theoretical and the applied is reflected in the career goals of the current group of PMC students. Both industrial and teaching career aspirations are represented. We expect that a similar diversity of career goals will be maintained in future PMC teams.

With this introduction on why process control and the PMC program at Lehigh are exciting to us, let's examine the philosophy, the people, the technical program, and the environment of PMC.



R. Donald Bartusiak received his BS from the University of Pennsylvania and his MS from Lehigh University. He is currently completing PhD studies at Lehigh. Before returning to graduate school, he worked as a research engineer for Bethlehem Steel Corp. His industrial experience also includes employment with Exxon Chemicals. His research interests and publications are in the areas of nonlinear process control and environmental engineering. (L)

Randel M. Price is a graduate student at Lehigh University. He has a BSChE from the University of Missouri-Columbia and an MSChE from the University of Arkansas. Prior to graduate school, he worked for the process engineering department of Conoco Inc. (R)

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As a result of the industry/academia partnership, the research work carried out by the students is neither all theoretical nor all applied, but is a delicate balance of both . . . students can be confident that their topic is novel and challenging.

THE PHILOSOPHY

Prior to establishing PMC, Lehigh faculty, in collaboration with industrial representatives, assessed the research needs in the area of process modeling and control. This assessment recognized that rapid technological advances are driving engineering towards cross-disciplinary interaction. It identified several important trends that have already affected, and will continue to affect, the chemical, petroleum, petrochemical and biochemical industries in the next decade. These trends, detailed below, justified the start-up of an intensive research effort.

- The trend to **improve the production efficiencies of existing chemical plants** has increased the need for more effective dynamic models, for improved real-time process measurements, and for more practical techniques for synthesizing multivariable, nonlinear and optimizing control structures. Research activities in this area have already been undertaken, but there still exists the strong need for practical, comprehensive methods that industry can effectively use.
- Efforts to **develop new technologies and processes** in growth fields, such as biotechnology and polymer engineering, have created the need for quickly constructing new process models and for developing more reliable control strategies. Modeling and control strategies in this area have barely scratched the surface of this very important problem. Traditional solutions influenced by past experiences are clearly not adequate. Novel ideas are needed in postulating the appropriate research problems and in providing fresh approaches for their solution.
- Increased process complexity, together with **strict industry and governmental standards for safety and the environment**, require more reliable methods for alarm system analysis, system design, and for new process fault diagnostic methods with predictive capabilities. Although industry has applied these concepts quite effectively with in-house approaches, there is a need for more systematic methods for the design and safe operation of the tightly integrated processes we will use in the future.
- Rapidly evolving technologies for **low-cost computer designs and VLSI systems fabrication** are creating new opportunities to apply powerful computer hardware and software for process control including real-time integrated plant transient simulation and optimization.
- Continuing advances in our ability to make **more accurate measurements of process variables**, especially under complex or harsh conditions, open up many possibilities for better understanding of process behavior and lead to improved techniques for process optimization and control. Research opportunities, for example, with respect to measurements in the processing of polymers and in biotechnology, are very numerous.

- Industry has **growing requirements for well-educated engineers** who possess a combined understanding of chemical process technology, up-to-date modeling and control approaches, and methods and theory for solving challenging process related problems. Furthermore, the growing use of computers in industry, coupled with the rapidly increasing power and distributed nature of the computer, is fundamentally altering the process of design, engineering, and process operation as well as the manpower needs of industry.

These six trends define the research mission of Lehigh's Chemical Process Modeling and Control Research Center.

THE PEOPLE

The cross-disciplinary nature of the PMC process control research effort is reflected in the human resources of the center. Of the sixteen faculty members participating in the center (Table 1), eleven are affiliated with the chemical engineering department, two with mechanical engineering, two with industrial engineering, and one with mathematics. Strong interactions exist between PMC, the Bioprocessing Research Institute, and the Emulsion Polymer Institute at Lehigh.

TABLE 1
PMC Research Center Faculty

Christos Georgakis, Director (ChE)	Andrew Klein (ChE)
William L. Luyben, Co-Director (ChE)	Janice A. Phillips (ChE)
Hugo S. Caram (ChE)	Matthew J. Reilly (ChE)
John C. Chen (ChE)	David A. Sanchez (Math)
Mohamed S. El-Aasser (ChE)	William E. Schiesser (ChE)
D. Gary Harlow (ME)	Harvey G. Stenger (ChE)
Arthur E. Humphrey (ChE)	Robert H. Storer (IE)
Stanley H. Johnson (ME)	John C. Wiginton (IE)

Two post-doctoral researchers are currently involved with furthering the work on specific research projects and with defining new projects. We also have three visiting research engineers from PMC industrial sponsors.

At present, twelve graduate students are enrolled in the activities of the center—eleven through the chemical engineering department and one through mechanical engineering. Two students will leave in 1987 with MS degrees, while the remaining ten are working towards the PhD. It is an international group. Some of the students have industrial experience, but most do not.

A special human resource of PMC is the close personal involvement of the company sponsors of the center. The twice-yearly meetings of the PMC Industrial Advisory Committee provide an opportunity for

both formal and informal exchanges between the students and the practicing engineers. Direct lines of communication between students and practitioners invariably result from these meetings. In fact, essentially all of the PMC thesis committees include a member from industry.

THE TECHNICAL PROGRAM

The typical initial stages of the graduate student's program are dominated by course work. As evidence of Lehigh's emphasis on process control, the advanced level control courses are all cross-listed by the chemical, mechanical and electrical engineering departments. The core advanced courses include state-space and optimal control, multivariable control, process identification, and stochastic control. These courses supplement undergraduate courses in introductory process control and in sampled-data control. In addition, topical seminars are periodically offered, for example, on nonlinear control.

The choice of a graduate research topic is intimately related to the research projects of the PMC center. The vast majority of research undertaken by the center is of a generic nature addressing major research challenges not fully addressed and resolved in the process control literature. A listing of the ten generic research projects currently active is provided in Table 2. Typically, thesis topics derive from these generic research projects.

The charter of PMC also provides for the conduct of suitable company-specific research projects. Although far less active than the generic research of the center, this work also provides potential topic areas for thesis research. As an example of the company-specific research, an MS thesis has been completed on "The Control of Low Relative Volatility Distillation Columns" making extensive use of real plant data from an industrial sponsor.

There is a liberal exchange of information among the projects. Students routinely share the software they have developed. Process models, including those derived from real industrial systems, are used by several researchers on different projects. Conversely, new control algorithms are tested in several different applications.

PMC-supported students are always able to publish their work in a timely manner according to the center's publication guidelines. Research is also reported at national meetings. Some restrictions pertain to the components of company-specific research projects involving proprietary information. PMC-supported students must file semi-annual progress reports to the Industrial Advisory Committee once they

TABLE 2
Current PMC Research Projects

1. Design of effective nonlinear controllers for chemical reactors
 2. Design of practical multivariable process controllers
 3. Design and control of energy-efficient distillation column systems
 4. Development of software for dynamic process simulation and control system design
 5. Bioreactor modeling, optimization and control
 6. Modeling and control of semi-continuous emulsion polymerization reactors
 7. Plant-wide control
 8. Expert multivariable control
 9. Batch reactor control
 10. Statistical quality control
-

become active in project work. In general, one formal presentation per year is given by each student to the industrial sponsor. Of course, less formal presentations on research plans and results are given with greater frequency within the PMC team.

THE ENVIRONMENT

A dramatic new development at Lehigh has occurred within the past year. A substantial portion of Bethlehem Steel's Homer Research Laboratory, located less than a mile from Lehigh's main campus, was acquired by Lehigh University. Acquisition of this beautiful facility nearly doubled the amount of space for research (laboratory and office) available to the university. PMC, the Chemical Engineering Department, the Bioprocessing Research Institute and the Emulsion Polymer Institute were among the first groups to occupy the new facility.

Foreshadowing the doubling of the research space, a doubling of the technical library space was accomplished during 1984-85. The E.W. Fairchild-Martindale Library currently houses 435,000 volumes, with a total capacity of 650,000 volumes. The Lehigh University library system receives more than 9,000 periodicals and serials. The library system fully utilizes computer database technology for cataloging and literature-searching. More than sixty-five full-time staff are available to serve the research needs of faculty and students.

In the area of computer resources, PMC researchers have access, through the campus-wide telecommunications network, to all university mainframes (CDC Cyber 850; Digital DEC-20 and VAX-8530; IBM 4381). Furthermore, PMC is equipped with its own CDC Cyber 810 computer—a \$500,000 grant from Control Data. For input/output, there are six Tek-

tronix 4109 graphics terminals, three Control Data 722 terminals, a Tektronix 4692 ink-jet plotter, and a Control Data 533 line printer dedicated to PMC users exclusively. Specialized software for process modeling and control research is available both from in-house development and from external sources. To further the work on expert systems, PMC has acquired a Symbolics 3620 machine with LISP and other advanced software systems. We plan to purchase a Sun Engineering Workstation this summer to support the Batch Reactor Control project. Public microcomputers are widely distributed about campus.

CONCLUSION

These are exciting times at Lehigh and the Chemical Process Modeling and Control Research Center. The chemical process industry is very much interested in stimulating research in process control, and in attracting engineers who are well-educated in the field. The university has responded to this challenge by initiating an intensive industry/academia cooperative research program to bring to light new knowledge in areas of practical importance. The net result for graduate students is that their research must satisfy conditions both of novelty and of practical reality. In our judgment, such a program yields engineers capable of succeeding in either academic or in industrial careers. □

ChE book reviews

MULTIPHASE SCIENCE AND TECHNOLOGY Volume 2

Edited by G. F. Hewitt J. M. Delhaye, N. Zuber
Hemisphere Publishing Co., New York 10016; 1986.
479 printed pages, \$62.50

Reviewed by

Y. Y. Hsu

University of Maryland

This book covers six subjects on multi-phase flow: *Chapter 1*, Flow Pattern Transition in Gas-Liquid Systems, Measurement and Modeling (A. E. Dukler, Y. Taitel); *Chapter 2*, A Critical Review of the Flooding Literature (S. George Bankoff, Sang Chun Lee); *Chapter 3*, A Comprehensive Examination of Heat Transfer Correlations Suitable for Reactor Safety Analysis (D. C. Greenoveld, C. W. Snoek); *Chapter 4*, Reboilers (P. B. Walley and G. F. Hewitt); *Chapter 5*, Flow of Gas-Solid Mixtures Through Standpipes

and Valves (L. S. Leung, P. J. Jones); *Chapter 6*, Core-Annular Flow of Oil and Water Through a Pipeline (R. V. A. Olieman, G. Ooms).

Chapter One on flow patterns in liquid-gas two phase flow is a comprehensive review of many years of significant contributions made by Professor Dukler and his colleagues at the University of Houston. Two-phase flow behavior is very much affected by the interfacial transport, which in turn is affected by the flow patterns. Determination of flow pattern has been of fundamental importance to two-phase flow studies. The authors' contribution is to treat flow pattern transition through modeling instead of the many empirical approaches previously prevalent in the industry. Dukler and Taitel are to be lauded for their more scientific and mechanistic approach to establish the flow pattern transition criteria. However, a major class of flow patterns that are absent are those related to vertical pipe or bundle with boiling/condensation which are very important in reactor safety analysis and in chemical processes.

The second chapter on flooding covers the subject relating to counter-current flow in a vertical channel. Since the flooding phenomena are very much affected by the entrance geometry—the boundary conditions (such as channel geometry heating or no heating), the steam or air flow conditions and physical properties (steam or air with water being subcooled or saturated), *etc.*—it is very difficult to give an unified and systematic treatment. The authors did a good job in this attempt.

After the analytical models, some experimental results and empirical correlations were introduced. In this section, unfortunately, a great deal of work carried out in reactor safety research was only briefly cited.

Chapter Three is a comprehensive examination of heat transfer correlation used for reactor safety analysis. The heat transfer package is the heart of thermal-hydraulic codes developed to predict the coolability of a reactor core during accidents and transients. Choice of proper heat transfer correlations for each heat transfer mode is the key to the success of a code. The authors of this chapter made a valiant effort to critically examine the heat transfer correlations and succeeded in giving a comprehensive review and provided readers with a fairly complete list of correlations currently being considered for reactor analysis. But the reviewer thinks that bundle data should be given more weight than tube data in assessing the correlations since bundle geometry is what is encountered in a reactor.

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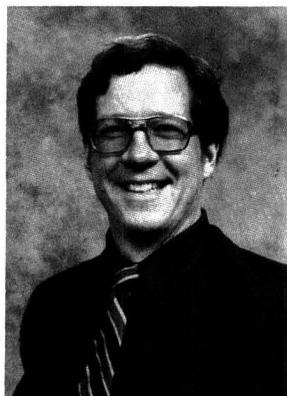
A program on . . .

ADVANCED COMBUSTION ENGINEERING

CALVIN H. BARTHOLOMEW
 Brigham Young University
 Provo, UT 84602

OUR NATION'S BASIC and high technology industries are highly dependent on an adequate supply of energy, the production of which depends upon combustion technology. The future survival of these industries will hinge on the ability to utilize more efficiently, through advanced combustion technology, our nation's readily available, low-cost fuel resources.

There are unfortunately several formidable roadblocks threatening the realization of these critically needed developments: (1) commitment of combustion-based industries to out-dated technologies, (2) environmental and operational problems in the utilization of low-cost, low-grade fuels, (3) insufficient understanding of combustion fundamentals, and (4) lack



Calvin H. Bartholomew received his BS degree from Brigham Young University and his MS and PhD degrees in chemical engineering from Stanford University. He spent a year at Corning Glass Works and a summer at Union Oil as a visiting consultant before joining the chemical engineering department at Brigham Young University in 1973. He is presently professor, head of the BYU Catalysis Laboratory, and Associate Director of the Advanced Combustion Engineering Research Center. Recipient of the Karl G. Maeser Research Award, he has authored over 70 scientific papers and 5 major reviews in the fields of heterogeneous catalysis and catalyst deactivation. His major research and teaching interests are heterogeneous catalysis, char combustion, kinetics and reactor design, Moessbauer spectroscopy, surface science, and air pollution control.

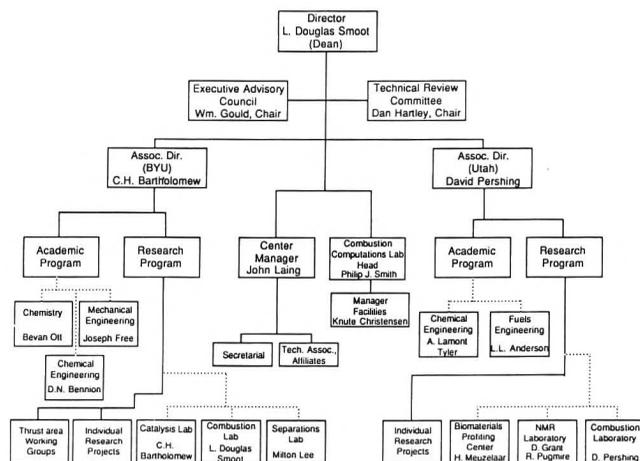


FIGURE 1. Management structure of the Advanced Combustion Engineering Research Center

of communication, collaboration and cooperation among investigators in academic, industrial and governmental research and development communities.

To address the removal of these roadblocks, the Advanced Combustion Engineering Research Center (ACERC) was established in the summer and fall of 1985 as a cooperative effort among Brigham Young University (BYU), the University of Utah (U of U), two national laboratories (Sandia National Labs and Los Alamos National Labs), and 23 industrial/research organizations located throughout the United States. The departments of chemical engineering (BYU and U of U), chemistry (BYU and U of U), fuels engineering (U of U), and mechanical engineering (BYU) were involved in the formation of this new center. Headquarters were established at BYU. The organization of the new center, consisting of a Directorate, an Executive Advisory Council and Technical Review Committee, is illustrated in Figure 1. Members of the management team consisting of the directorate and coordinators for research, education, and information dissemination are listed in Table 1, while members of the Executive Advisory Council are listed in Table 2. Listed in Table 3 are companies and

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laboratories which have subscribed as technical partners of the center.

In the fall of 1985, proposals were submitted to the National Science Foundation (NSF) and the State of Utah for funding. On May 1, 1986, BYU and the U of U were jointly awarded a \$9.7 million 5-year grant from NSF as part of its Engineering Research Centers Program. This award was one of five selected from 102 proposals submitted by 74 institutions in fall 1985. Also receiving grant awards from NSF in the 1985-86 round were Carnegie-Mellon University, Uni-

TABLE 1
ACERC Management

Director	
L. Douglas Smoot	
Dean of Engineering and Technology Head of the Combustion Laboratory	
Associate Directors and Research Coordinators	
BYU	U of U
Calvin H. Bartholomew Professor of Chem. Eng. Head of the Catalysis Lab	David W. Pershing Professor of Chem. Eng. Assoc. Dean of Grad. School
Academic Coordinator	
Calvin H. Bartholomew Professor of Chem. Eng.	David M. Bodily Professor of Fuels Eng. Assoc. Dean of Mines & Min.
External Relations Coordinator	
John C. Laing Manager, ACERC	Ronald J. Pugmire Prof. of Fuels Eng. Assoc. Vice Pres. of Res.

TABLE 2
Executive Advisory Council

- **William Gould**, Chairman, Retired Chief Executive Officer of Southern California Edison and EPRI Chairman
- **Christian Bolta**, Director of Technology Strategy, Combustion Engineering, Inc.
- **Dan Hartley**, Vice President of Sandia National Laboratories
- **George Hill**, Professor of Chemical Engineering at the University of Utah and former Director of the office of Coal Research and EPRI
- **Eric Reichl**, Consultant and Retired President of the Conoco Coal Development Company
- **Adel Sarofim**, Professor of Chemical Engineering, MIT
- **George Watkins**, Executive Director of the Empire State Electric Energy Research Corporation

There are unfortunately several formidable roadblocks threatening the realization of these critically needed developments . . . To address the removal of these roadblocks, the Advanced Combustion Engineering Research Center was established . . . in 1985 . . .

versity of Illinois-Urbana, Lehigh University and Ohio State University.

In addition to the funds from NSF, the center will receive approximately \$3.5 million from the two universities, \$500,000 from the State of Utah, and over \$500,000 from private industry, for a total of about \$14 million for the five years. During the first year the total ACERC budget was \$3.2 million.

RESEARCH OBJECTIVES AND PROGRAM

Objectives. Since combustion is a very broad field, a focus is essential in order to make a significant contribution. ACERC's research program has been designed to address the most significant research priorities for U. S. competitiveness in combustion technology while removing the roadblocks mentioned above. *The principal objective of ACERC is to develop and implement, within 5 years, advanced computer-*
Continued on page 216.

TABLE 3
Technical Partners of ACERC

TECHNICAL ASSOCIATES

- Advanced Fuel Research, Inc.
- Babcock and Wilcox
- Combustion Engineering, Inc.
- Consolidated Coal Co.
- Convex Computer Corp.
- Electric Power Research Institute
- Empire State Electric Energy Research Corp.
- Foster-Wheeler Development Corp./IHI (Japan)
- Gas Research Institute
- Morgantown Energy Tech. Center
- Pittsburgh Energy Tech. Center
- Tennessee Valley Authority
- Utah Power and Light Co.

TECHNICAL AFFILIATES

- General Motors Corp. (Alison Gas Turbine Div.)
- Chevron Research Co.
- Corning Glass Works
- Dow Chemical USA
- General Electric Co.
- Los Alamos National Laboratory
- Pyropower Corp.
- Questar Development Corp.
- Shell Development Co.
- Southern California Edison

An experiment in . . .

LIQUID-PHASE ADSORPTION FUNDAMENTALS

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Laramie, WY 82071

ADSORPTION PROCESSES ARE important in the removal of organic contaminants from wastewaters and municipal drinking water supplies, in the removal of solvents and odor compounds from gas streams, in the drying of air, *etc.* The adsorbent employed may be activated carbon, synthetic resins, silica gel, *etc.*

An adsorption experiment has been developed and successfully run in our unit operations laboratory course at the University of Wyoming. It involves the liquid-phase adsorption of an organic compound from aqueous solution on activated carbon, but is relevant to adsorption processes in general.

In designing the experiment several goals were set: (1) it had to be capable of being completely run in four hours or less, (2) it should demonstrate the applicability of both the Langmuir and Freundlich isotherm equations to equilibrium data, and (3) it



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should familiarize the student with both batchwise and continuous fixed-bed types of operations. In addition, the component to be adsorbed should be reasonably water-soluble so that aqueous solutions could be employed, and it should be colored so that its removal by batch adsorption and its breakthrough behavior in fixed-bed operation be *visible* to the student. This requirement also allowed for easy measurement of the solute's concentration colorimetrically. One problem often encountered with colored solutes, however, is that their color intensity is a function of solution pH. And, since contact with activated carbon can change the pH of an aqueous solution and thereby alter the solute's color intensity (even at constant solute concentration), buffering of the aqueous solution to be used was considered to be necessary.

After some trial-and-error, the stock solution for the experiment was chosen to be a 0.30 g/liter solution of 2,4 dinitrophenol (DNP) in distilled water, buffered to a pH of 7.4 by the addition of 1.184 g/liter KH_2PO_4 and 4.289 g/liter NaHPO_4 . The DNP (Eastman Kodak Chemicals brand) contained around 15% moisture, which was *included* in the 0.30 g/L portions weighed out. A Pye Unicam Model 6-550 UV/Visible spectrophotometer was used in the visible mode at a wavelength of 480 nm with standard 1 cm \times 1 cm \times 4.5 cm matched glass sample cells (one cell was a reference cell containing distilled water; the other was the "sample" cell) to analyze all samples generated in the experiment for DNP concentration (the stock solution absorbance was around 0.600). Beer's Law was found to be obeyed for DNP sufficiently well over the range of concentrations involved in the experiment, *i.e.*, the DNP concentrations were proportional to the visible light absorbance values given by the spectrophotometer. The stock solution was deep-yellow in color.

The carbon used was Pittsburgh CPG activated

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**Adsorption processes are important in the removal of organic contaminants from wastewaters . . .
An adsorption experiment has been developed and successfully run in our unit operations laboratory
course . . . It involves the liquid-phase adsorption of an organic compound from aqueous
solution on activated carbon, but is relevant to adsorption processes in general.**

carbon, sieved to 28/40 mesh for the fixed-bed experiments and ground to less than 325 mesh for the batch (equilibrium) experiments. The carbon was heated in an oven at 150°C for 24 hours prior to use and then kept in closed glass jars (this prevents contamination by stray gas-phase adsorbates).

BATCH (EQUILIBRIUM) EXPERIMENTS

Approximately six samples containing roughly 0.005 to 0.030 grams of the powdered carbon (at essentially equally spaced weight intervals) were weighed into new dust-free liquid scintillation vials (Wheaton 20 mL borosilicate glass vials, from Cole-Parmer Instrument Co., Chicago, Cat. No. J-8918-02) using a Mettler AE 160 digital balance capable of weighing to 0.1 mg. Then 10 mL of the stock DNP solution was added to each vial using a standard volumetric pipette. The vials were capped with the caps that came with them (these had Poly-Seal conical seals in them) and taped (with cellophane tape) onto the bed of a shaker bath (Precision Scientific, Model 25, Chicago) (water omitted) set at 100 oscillations/minute. Any other suitable shaking device would work just as well. After one hour of shaking, the vials were removed and let stand for about ten minutes to allow most of the powdered carbon to settle. (It was proved separately that equilibrium is reached in about twenty minutes, for < 325 mesh carbon.)

Meanwhile, six filter units each consisting of a 13 mm diameter Millipore HAWP 0.45 μm pore size membrane filter in a 13 mm size Swinny filter holder (both available from the Millipore Corporation, Bedford, MA) were prepared. About 15 mL of each sample supernatant solution was taken up into a 20 mL plastic syringe which was then attached to a filter holder, and the solution was filtered to remove the remaining carbon particles. The first few mL were discarded (membrane "debris" sometimes flushes off into the first portion of the filtrate) and the remainder was collected in a small beaker (covered) or clean capped scintillation vial for subsequent colorimetric analysis.

For each sample, the DNP concentration was computed from: concentration (g/L) = 0.30 x (sample absorbance at 480 nm/stock solution absorbance at 480 nm). This concentration, C_A , was used in the mass balance $q_A^* W = V (C_{AO} - C_A)$ where W = grams of

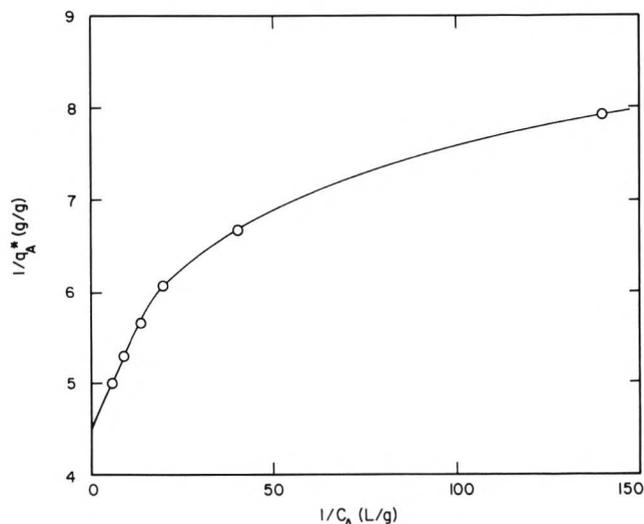


FIGURE 1. "Linearized" Langmuir equation plot of the equilibrium data, which should yield a straight line if K and Q are constant.

powdered carbon used, V = volume of solution used (0.01 liter), and C_{AO} = initial DNP concentration (0.30 g/liter), to compute the equilibrium carbon-phase concentration q_A^* (g DNP/g carbon).

BATCH (EQUILIBRIUM) RESULTS

Since the Langmuir isotherm equation

$$q_A^* = KQ C_A / (1 + K C_A) \quad (1)$$

can be linearized to the form

$$\frac{1}{q_A^*} = \frac{1}{Q} + \frac{1}{KQ C_A} \quad (2)$$

the data were plotted in the form of $1/q_A^*$ versus $1/C_A$ in the hopes that they could be fit with a straight line to give an intercept of $1/Q$ and a slope of $1/KQ$, from which K and Q (the value of q_A^* reached as $C_A \rightarrow \infty$, *i.e.*, the monolayer adsorption capacity of the carbon for DNP) could be determined. As Figure 1 shows, such a straight-line fit was impossible (*i.e.*, the data simply do not fit the Langmuir model).

The q_A^* versus C_A data were also plotted on log-log paper, since the Freundlich isotherm equation is

$$q_A^* = k C_A^{1/n} \quad (3)$$

hence

$$\log q_A^* = \log k + (1/n) \log C_A \quad (4)$$

Students always try to get an "intercept" on such a plot, but this is impossible, of course. They should

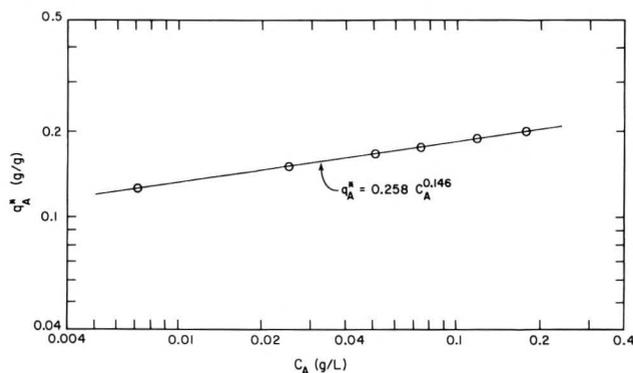


FIGURE 2. Linearized Freundlich equation plot of the equilibrium data.

simply pick two points near the ends of the best fit straight line, and insert these two (q_A^* , C_A) pairs into the last equation, thereby generating two equations from which the two unknown parameters k and $1/n$ can be determined. As Figure 2 shows, the data fit the Freundlich expression extremely well. This is consistent with the author's and other investigators' previous experience in measuring liquid-phase equilibria for organic compounds adsorbing on activated carbon, in which it has been repeatedly observed that the Freundlich equation fits such data very well (see the references listed at the end of this paper).

Although the Langmuir equation obviously does not fit the equilibrium data, the data for the four highest C_A points (*i.e.*, for the four lowest $1/C_A$ points in Figure 1) can be fit reasonably well to a straight line, from which one obtains $Q = 0.221$ and $K = 53.7$. Figure 2, for the Freundlich equation, gives $k = 0.258$ and $1/n = 0.146$. Plots of Eqs. (1) and (3) with these parameter values give the comparison to the equilibrium data shown in Figure 3. Obviously, the Freundlich equation fits essentially exactly, while the Langmuir equation fits somewhat well at high C_A and poorly at low C_A , as one would expect considering how Q and K were obtained.

FIXED BED EXPERIMENT

Four grams of the 28/40 mesh Pittsburgh CPG carbon were loaded into a 0.9 cm I.D. by 15 cm long chromatography column (type K 9/15 from Pharmacia Fine Chemicals, Inc., Piscataway, NJ). The empty column, with the top inlet header unscrewed, was filled with distilled water (with the outlet line clamped), and small portions of the carbon were dropped into the column successively until the column was packed with the full 4 grams of carbon. This technique prevents any trapping of air bubbles in the bed. While some classification of the carbon particles occurs as they fall through the water, gross classification of the bed is avoided by adding the carbon in small batches with a spatula and waiting for each batch to settle. The water level in the column rises as one does this, so the clamp on the column outlet line must be periodically opened to drain off some of the water and keep it from overflowing out of the top of the column. Once

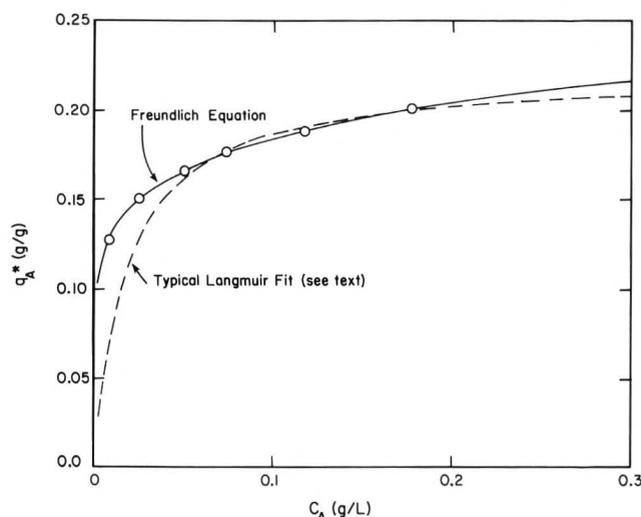


FIGURE 3. Comparison of equilibrium data with the Freundlich equation, and with a Langmuir equation derived from fitting the high C_A data.

the column was packed, the top inlet header was screwed onto the column. The stock DNP solution, 3 liters of which were contained in a standard one-gallon glass jug, was pumped to the column at 25 mL/minute using a Masterflex Unified Variable Speed Model 7523-10 tubing pump drive fitted with a number 7014 Standard Pump Head, and number 14 silicone rubber tubing (Cole-Parmer Instrument Co., Chicago).

The pump was turned on briefly enough to bring the DNP solution to the end of the tubing, which was

then attached to the column inlet header. At "time zero," a stopwatch was started and the pump was re-started. Effluent from the column was collected in a 1000 mL graduated cylinder and, as each successive 100 mL mark was reached, a spectrophotometer cell was held under the effluent line for long enough to collect about 2.5 mL of effluent. The sample absorbance was then measured colorimetrically (any drops of sample on the cell outside surfaces were first dried off using Kimwipes). The reference cell was checked

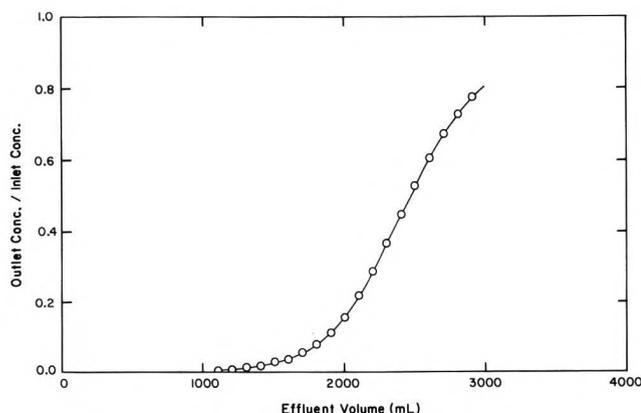


FIGURE 4. Effluent curve behavior for the experiment.

each time to see that its absorbance read 0.000. The sample was then dumped back into the collection cylinder. When the first 1000 mL cylinder was full, a second one was used to replace the first one, and the first one was dumped. The cylinders were alternated this way, with sample measurements each 100 mL, until the effluent concentration exceeded 75% of the inlet concentration. The fixed bed experiment was then shut down and the data were plotted as C_A versus total effluent volume.

FIXED BED RESULTS

Figure 4 shows the breakthrough curve obtained from the fixed-bed part of the experiment. If ideally-sharp breakthrough behavior were to exist, a step function would have been obtained at a point where a vertical line passes through the point $C_A = 1/2 C_{A,feed}$ (assuming a symmetrical breakthrough curve). The total effluent volume corresponding to this step function can be seen to be about 2460 mL, and hence the total column capacity for DNP is thus (2.46 liters) (0.30 g/liter)/4.0 g carbon = 0.185 g DNP/g carbon. However, inserting $C_A = 0.30$ g/liter into the Freundlich equation gives a q_A^* value of 0.235. The

reason why the 0.185 is about 21% too low is that the effluent curve is actually *not* symmetrical but would show significant "tailing" if it had been followed further. Hence, the proper position to place the step function for the ideal case would be at an effluent volume greater than 2460 mL. This would raise up the calculated 0.185 value and give better agreement with the "ideal saturation capacity" value calculated from the Freundlich equation.

Nevertheless, the step-function replacement of the actual breakthrough curve does give a rough approximation to the column's ideal capacity. Of course, in actual operation, a fixed-bed system would be shut down as soon as the outlet concentration is just a few percent (*e.g.*, 5%) of the inlet concentration. The only reason we followed the breakthrough curve so far in this experiment was to allow the students to see what the curve looks like at later stages, and to allow them to compare (at least approximately) the total DNP capacity from this dynamic column technique to values predicted by batch equilibrium experiments.

COMMENTS

With a group of three students performing this experiment, we start the batch sample part first. Then, while the samples are shaking (one hour) we begin the column part. Sometime during the column run, the batch samples are ready for filtration, so the filtration is carried out by one of the students, and the filtrates are kept aside for analysis after the column run is over.

In their reports, the students are asked to discuss general principles of adsorption, particularly low temperature physical adsorption (*via* van der Waals type forces) on activated carbon. They are also asked to discuss how activated carbon is usually made, and its properties (internal surface area, pore-size distribution, *etc.*).

Overall, the experiment and subsequent student reports are effective in conveying most of the basic principles of physical adsorption processes.

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The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested as well as those that are more traditional in nature, which elucidate difficult concepts. Please submit them to Professor H. Scott Fogler, ChE Department, University of Michigan, Ann Arbor, MI 48109.

MODELING OF HEAT TRANSFER WITH CHEMICAL REACTION

Cooking a Potato

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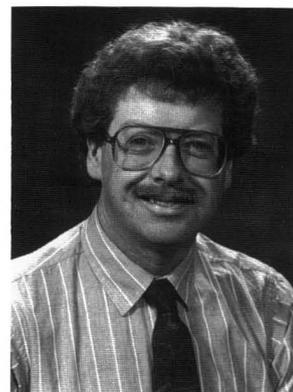
PROBLEM

THE COOKING OF a potato in a hot water bath may be readily described by combining a model of transient heat transfer in a sphere (with convective boundary conditions) and kinetic data given by Personius and Sharp [1] for the rate of change in tensile strength in potato tubers as a function of temperature. A computer program may be written which uses finite difference methods to solve the transient heat transfer equation. When these results are combined with kinetic data, transient tensile strength profiles may be generated. The cooking of the potato can therefore be simulated. The model is readily verified with a minimum of laboratory time and equipment.

CHEMICAL BASIS: COOKING A POTATO

Roughly 60-80% of the dry matter of a potato tuber is starch. Potato starch is a mixture of two polymers of α -D-glucose, amylose and amylopectin. Amylose (20% of potato starch) is a linear unbranched chain of α -D-glucose units joined by $\alpha(1 \rightarrow 4)$ acetal linkages. Amylopectin is a branched polysaccharide with $\alpha(1 \rightarrow 6)$ branch points. Native amylose and amylopectin polymers have molecular weights in the millions.

Within the potato tuber, starch occurs as microscopically visible granules which are 15-100 microns in diameter and oval in shape. Thin sections of starch granules reveal them to be highly organized consisting



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of concentric layers. Within these layers, starch molecules associate through extensive hydrogen bonding between parallel linear segments.

The microscopic appearance of starch granules changes markedly upon heating. In cold water, isolated starch granules will take up 20-30% of their weight in water. This association is reversible *i.e.*, the granule can be recovered in its original state upon drying. At about 65°C, starch granules will swell rapidly, taking up large amounts of water (up to 25 times the original weight of the granule). This swel-

ling process, termed gelatinization, is irreversible. Heating disrupts regional hydrogen bonding between adjacent starch segments, replacing starch-starch association with starch-water association. Upon cooling, the hydrated segments are no longer free to hydrogen bond to other starch segments. Starch granules in plant tissue undergo gelatinization upon heating by taking up cellular water and/or water from their environment if heated by steam or hot water.

The individual potato cell is surrounded by a rigid cell wall consisting principally of cellulose interwoven with pectins. Cellulose is a high molecular weight polysaccharide in which the repeating unit is β -D-glucose. Pectins are a complex mixture of polysaccharides of galacturonic acid or its methyl ester. These pectic substances are regarded as the cementing substances which hold plant cells together.

The softening that occurs upon cooking of fruits and vegetables is partially the result of depolymerization of pectic substances. Depolymerization of pectins occurs in all types of cooking processes. The common observation that potatoes cook faster when immersed in water than if steamed or baked is attributed to diffusion of pectin degradation products out of the tissue and their solubilization in the cooking water.

When potatoes are cooked, the starch they contain is gelatinized and the water contained within the cell is adsorbed in the process. The cells become filled by swollen starch granules, applying pressure to the cell wall if sufficient starch granules are present. The cell walls of individual cells normally remain intact; however, weakening of the cell walls by depolymerization of pectins makes the cell wall somewhat flexible. Therefore, if sufficient starch is present, the cell (which is normally box-like in shape) becomes roughly spherical. The change in shape further weakens the cementing forces which bind cells together by limiting surface-surface contact.

A potato which is regarded as being of high quality for cooking will have a mealy texture upon being baked, boiled, steamed or fried. Mealiness is that quality of being soft, dry, and easily crumbled. Mealiness in a cooked potato results from an ease of separation of individual cells. A good cooking quality potato will therefore be one which contains a high proportion of cells which possess sufficient starch content to cause cellular and interstitial water to be adsorbed and to cause distortion of the cell shape to something more spherical when gelatinization takes place. The absence of sufficient starch leads to a hard, soggy texture even after cooking. In addition, a high quality cooking potato will have a high proportion of cells which are small enough to resist rupturing when the

The cooking of a potato in a hot water bath may be readily described by combining a model of transient heat transfer in a sphere (with convective boundary conditions) and kinetic data for the rate of change in tensile strength in potato tubers as a function of temperature.

cooked tuber is mashed. Rupturing of cells results in release of swollen starch granules which gives the cooked potato a sticky, waxy texture.

KINETICS OF COOKING A POTATO

Personius and Sharp [1] have examined the adhesion of potato tuber cells as influenced by temperature. In their experiments, whole potato tubers were coated with a thin layer of rubber paint and held in a constant temperature water bath. The rubber paint prevented the exchange of water and salts between the tuber and water bath. Thermocouples measured the temperature of the potato centers. After the potato centers reached the temperature of the water bath, potato tubers were removed at various times and the tensile strength of sections was obtained.

From data reported by Personius and Sharp, the rates of decrease in tensile strength as a function of incubation temperature were determined in order to prepare an Arrhenius plot (see Figure 1). The primary assumption made here was that these rates are roughly equivalent to those which would have been

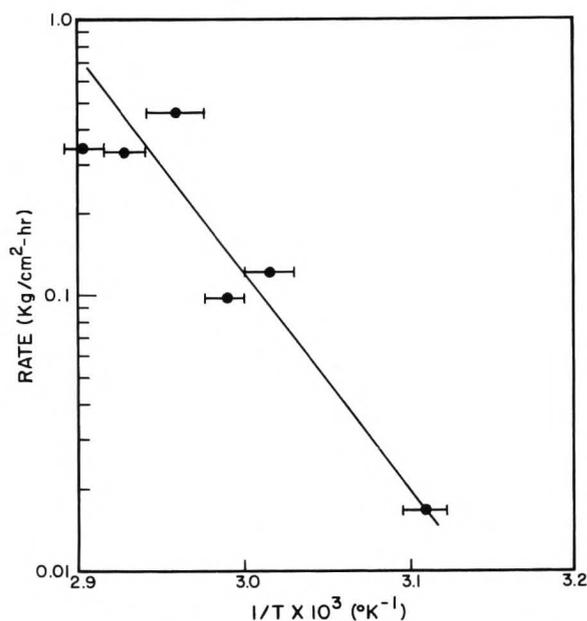


FIGURE 1. Arrhenius plot of data of Personius and Sharp [1]

observed if the potatoes warmed to the incubation temperatures instantly. The effect of heat during warming time on these rates is unknown.

The rate equation for the cooking process may be expressed as follows

$$-\frac{d(TS)}{dt} = k f(x) = k_0 e^{-E_a/RT} f(x) \quad (1)$$

where TS = tensile strength (kg/cm²)

k = a rate constant

k₀ = frequency factor

E_a = energy of activation

R = universal gas constant

T = temperature (°K)

f(x) = some function of the condition of the potato, assumed to be constant during the cooking process

In logarithmic form the rate equation becomes

$$\ln \left(-\frac{d(TS)}{dt} \right) = \frac{-E_a}{RT} + \ln \left(k_0 f(x) \right) \quad (2)$$

From the Arrhenius plot the energy of activation and the factor [k₀f(x)] were determined to be 32500 cal/mole and 2.85 × 10²⁰ kg/cm²-hr, respectively. Substituting these values into the rate equation and integrating we have

SOLUTION

Modeling the Cooking of a Potato

The process to be modeled is the cooking of a potato in a hot water bath under conditions of forced convection. Transient temperature profiles in the potato may be produced by numerical solution of Eq. (A1) (see Appendix) which describes unsteady-state heat conduction in a sphere of constant thermal conductivity, heat capacity and density, heated by a surrounding fluid. The numerical solution of this equation is detailed in the Appendix utilizing the Crank-Nicolson finite difference method. Coupling this solution with the integrated form of the rate equation describing the change in tensile strength in a potato tuber as a function of time and temperature (Eq. 3) allows transient tensile strength profiles to be generated.

A FORTRAN program which produces transient tensile strength profiles in a cooking potato is available from the author. The program incorporates the following assumptions:

$$TS_0 - TS_t = \left[2.85 \times 10^{20} \exp \left(\frac{-1.64 \times 10^4}{T} \right) \right] t \quad (3)$$

where TS₀ = tensile strength at t = 0

TS_t = tensile strength at time t

T = temperature (°K)

t = time (hrs)

Based on data presented by Personius and Sharp, a value of 6.8 kg/cm² may be taken as the average tensile strength of a raw potato tuber (TS₀).

Personius and Sharp noted that the limiting value of the tensile strength of a potato heated in a constant temperature water bath was somewhat dependent upon the incubation temperature. Above 73°C the limiting tensile strength was 0.4 kg/cm². Below 49°C relatively little change in tensile strength occurred over long periods of incubation. Between 49°C and 73°C there was observed to be a linear relationship between incubation temperature and limiting tensile strength. In this range the limiting tensile strength can be given by Eq. (4), derived from the data given by Personius and Sharp

$$TS_1 = -0.24 T_i + 17.8 \quad (4)$$

where TS₁ = limiting tensile strength (kg/cm²)

T_i = incubation temperature (°C)

- The potato is spherical with a diameter of 3 inches.
- The heat capacity and thermal conductivity of the potato are assumed to be approximately that of water (the potato is roughly 80% water).
- The specific gravity of the potato is approximately 1.08.
- The potato is coated with a thin layer of rubber paint or rubber cement to prevent loss of salts or exchange of water with its environment (a requirement for validity of Personius and Sharp's data).

The basic sequence of calculations in this program is as follows (see appendix):

1. The cooking temperature and value of the parameter hR₀/k are assigned. Under conditions of forced convection the heat transfer coefficient, h, is estimated to be 700-2000 W/m²-°C using the correlation given by Vliet and Leppert [2]. These values correspond to a relative fluid velocity over the sphere of 0.1-1.0 ft/s. It may be readily demonstrated that temperature profiles in the cooking potato are relatively insensitive to hR₀/k when hR₀/k > 40. For

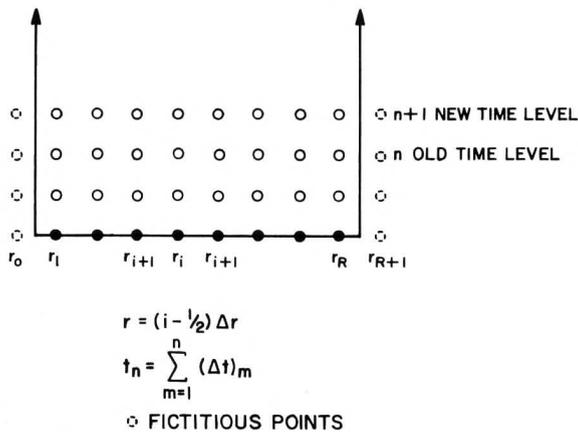


FIGURE 2. Grid points for finite difference calculations

a 3 in. diameter potato with a thermal conductivity equal to that of water, this corresponds to a heat transfer coefficient of 540 W/m²·°C.

2. As shown in Figure 2, *n* is the time level index and *i* the index of points in space where the dimensionless temperature *u* and the subsequent tensile strength are calculated by the program. Initially the dimensionless temperatures *u*_{*i*,0} for *i*=1,20 are set to zero and tensile strengths set to 6.8 kg/cm², the average tensile strength of a raw potato. Each set of dimensionless temperatures *u*_{*i*,*n*} are then calculated in turn (*n*=1,2,3,...) from the finite difference equation described in the Appendix. At all points *i* for each set of time levels *n* and *n*+1 the average temperature (TAVG) between the "old" and "new" time levels is calculated.
3. Utilizing Eq. (3) the change in tensile strength (ΔTS) at each point *i* which results from cooking at

TAVG for a length of time equal to the Δ*t* between the *n*th and (*n*+1)th time level is then calculated. At each point *i* these changes in tensile strength are added to all of those changes in tensile strength which took place between *t*=0 and the *n*th time level. These summations for all points *i* are then subtracted from 6.8 kg/cm², the tensile strength of a raw potato tuber. The result is then the tensile strength at all points *i* at the (*n*+1)th time level.

4. Next the lower limits are applied to the tensile strength at any point *i* at the (*n*+1)th time level according to the cooking temperature (TAVG) over the time interval of *n* to *n*+1. If TAVG < 49°C, the lower limit of TS is 6.8 kg/cm². If TAVG > 73°C, the lower limit is 0.4 kg/cm². If 49°C < TAVG < 73°C, the lower limit is given by Eq. (4).
5. The (*n*+1)th time level becomes the *n*th level and calculations are repeated giving tensile strength profiles as a function of radial distance from the center and time.

Sample outputs of dimensionless temperature and tensile strength profiles from this program are shown graphically in Figure 3(a-b) and Figure 4(a-b), respectively, for a 3 in. diameter potato cooking at 90°C with *hR*₀/*k* of 3.125 and 6400.

Testing the Model

Figure 4(b) may be taken as the predicted tensile strength profiles in a 3 in. potato cooking at 90°C in a hot water bath under conditions of forced convection (*hR*₀/*k* > 40). To test the model, ten Idaho baking

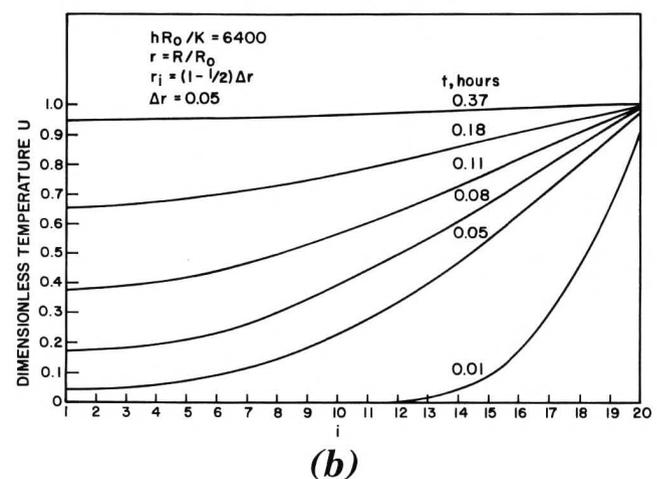
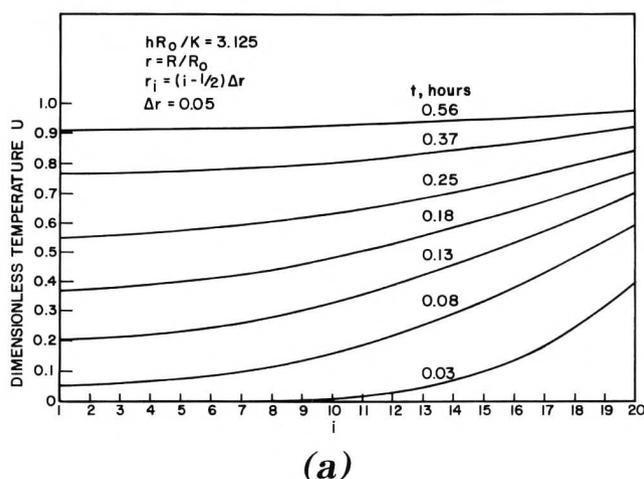


FIGURE 3. Transient dimensionless temperature profiles in a potato cooking at 90°C. *hR*₀/*K* = (a) 3.125, (b) 6400

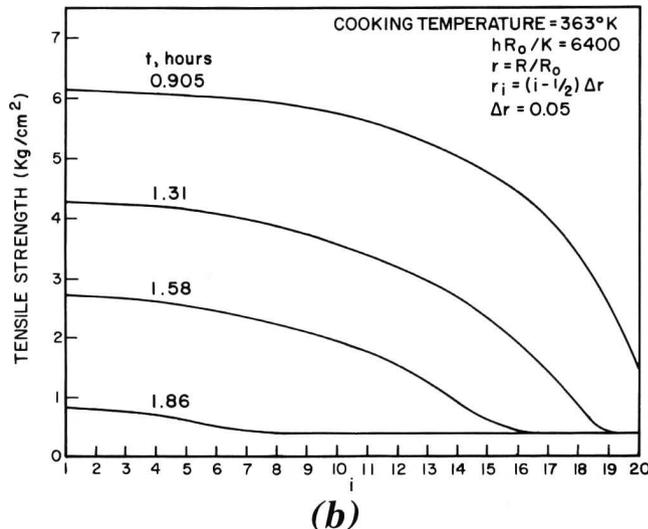
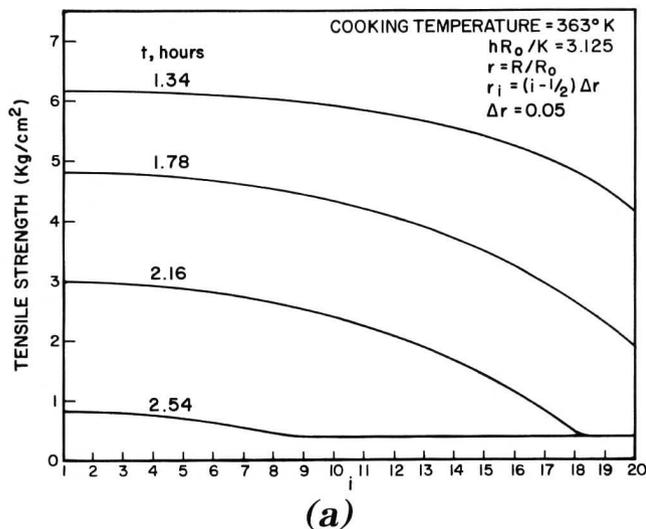


FIGURE 4. Transient tensile strength profiles in a potato cooking at 90°C. $hR_0/K =$ (a) 3.125 (b) 6400

potatoes were coated with a thin layer of rubber cement and heated in a water bath at 90°C. Water was circulated by means of a propeller stirrer. Potatoes were chosen to be as nearly spherical as possible and approximately 3 in. in diameter. The potatoes chosen were more accurately described as oblong measuring two by three inches. Potatoes were removed periodically, cut in half and an assessment made of the texture at various locations. The following observations are typical

Time (hours)	Observation
0	cooking started
0.25	outmost 0.1-0.3 cm cooking
0.50	outmost 0.5 cm mealy
0.75	outmost 0.8 cm mealy
1.00	cooking throughout but outmost 1-1.2 cm mealy
1.25	outmost 2 cm mealy
1.50	outmost 2.6 cm mealy
1.67	mostly cooked, still hard in center
1.75	potato cooked and mealy throughout

These results are in good agreement with the predictions of the model as given by Figure 4(b).

CONCLUSION

In the proposed problem/experiment students couple transient heat transfer with reaction kinetics to predict the course of the gelatinization of starch in a cooking potato. Students are introduced to numerical methods for the solution of partial differential equations and computer simulation of a chemical reaction under nonisothermal, unsteady-state conditions. Students can readily use the model to make predic-

tions and test the validity of those predictions in the laboratory with a minimum of time and equipment.

The proposed modeling exercise combines skills in mathematics, computer programming, heat transfer, and kinetics. The problem is challenging but manageable by a senior chemical engineering student.

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APPENDIX

Temperature Profiles in a Cooking Potato

The cooking of a potato in a water bath may be modeled after that of a sphere of constant thermal conductivity (k), density (ρ), and heat capacity (C_p) heated by a surrounding fluid. The differential equation for the temperature distribution, $u(r,t)$, in the sphere is given by Eq. (A1)

$$\frac{\partial^2 u}{\partial r^2} + \frac{2}{r} \frac{\partial u}{\partial r} = \frac{\partial u}{\partial t} \quad (A1)$$

The boundary and initial conditions are

$$\begin{aligned} u &= 0 && \text{for } t = 0, \text{ all } r \\ \frac{\partial u}{\partial r} &= 0 && \text{for } r = 0, \text{ all } t \\ \frac{hR}{k} (1 - u) - \frac{\partial u}{\partial r} &= 0 && \text{for } r = 1, \text{ all } t \end{aligned}$$

h = coefficient of heat transfer between the surface of the sphere and the bulk fluid

u , r and t are all dimensionless parameters defined as follows

$$u = \frac{T - T_i}{T_\infty - T_i} \quad \text{where } T_\infty = \text{bulk temperature of the fluid surrounding the sphere}$$

$$r = \frac{R}{R_0} \quad \text{where } R_0 = \text{radius of the sphere}$$

$$t = \frac{k}{R_0^2 \rho C_p} \hat{t} \quad \text{where } \hat{t} = \text{real time}$$

Eq. (A1) with accompanying boundary conditions may be solved numerically utilizing the Crank-Nicolson finite difference method. The two independent continuous variables (r and t) are replaced by discrete variables (also called here r and t) defined at points located on the grid shown in Figure 2.

The following finite difference analogs may be written

$$\left(\frac{\partial u}{\partial t}\right)_{i,n+1/2} = \frac{u_{i,n+1} - u_{i,n}}{\Delta t}$$

$$\left(\frac{\partial^2 u}{\partial r^2}\right)_{i,n+1/2} = \frac{1}{2} \left[\frac{u_{i+1,n} - 2u_{i,n} + u_{i-1,n}}{(\Delta r)^2} + \frac{u_{i+1,n+1} - 2u_{i,n+1} + u_{i-1,n+1}}{(\Delta r)^2} \right]$$

$$\left(\frac{\partial u}{\partial r}\right)_{i,n+1/2} = \frac{1}{2} \left[\frac{u_{i+1,n} - u_{i-1,n}}{2(\Delta r)} + \frac{u_{i+1,n+1} - u_{i-1,n+1}}{2(\Delta r)} \right]$$

Making these substitutions in Eq. (A1) results in the following finite difference analog

$$u_{i-1,n+1} + u_{i,n+1} \left[\frac{-2(\Delta t) - 2(\Delta r)^2 \left(\frac{i-1/2}{i-3/2}\right)}{\Delta t} + u_{i+1,n+1} \left(\frac{i+1/2}{i-3/2}\right) \right]$$

$$= -u_{i-1,n} + u_{i,n} \left[\frac{2(\Delta t) - 2(\Delta r)^2 \left(\frac{i-1/2}{i-3/2}\right)}{\Delta t} \right]$$

$$+ u_{i+1,n} \left[-\left(\frac{i+1/2}{i-3/2}\right) \right]$$

This equation applies for $2 \leq i \leq (R-1)$. In writing this equation for $i = 1$ or $i = R$, terms involving fictitious points ($u_{0,n+1}$ and $u_{0,n}$ or $u_{R+1,n}$ and $u_{R+1,n+1}$, respectively) are produced. Writing finite difference analogs for the boundary equations allows these terms to be eliminated.

$$\left(\frac{\partial u}{\partial r}\right)_{1/2,n} = \frac{u_{1,n} - u_{0,n}}{2} = 0$$

for all n . Therefore

$$u_{0,n} = u_{1,n} \quad \text{and} \quad u_{1,n+1} = u_{0,n+1}$$

For $i = 1$ we have then

$$u_{1,n+1} \left(\frac{3\Delta t + 2(\Delta r)^2}{\Delta t} \right) - 3u_{2,n+1} = u_{1,n} \left(\frac{2(\Delta r)^2 - 3\Delta t}{\Delta t} \right) + 3u_{2,n}$$

$$\frac{hR_0}{k} (1 - u) - \frac{\partial u}{\partial r} = 0$$

becomes

$$\frac{hR_0}{k} \left(1 - \frac{u_{R,n} + u_{R+1,n}}{2} \right) - \left(\frac{u_{R+1,n} - u_{R,n}}{\Delta r} \right) = 0$$

for all n . Replacing hR_0/k with \hat{k} gives

$$u_{R+1,n} = u_{R,n} \left[\frac{\hat{k}\Delta r - 2}{-\hat{k}\Delta r - 2} \right] - \left[\hat{k} / \left(\frac{-\hat{k}\Delta r - 2}{2\Delta r} \right) \right]$$

for all n .

Therefore for $i = R$ we have

$$u_{R-1,n+1} + u_{R,n+1} \left[\frac{-2\Delta t - 2(\Delta r)^2 \left(\frac{R-1/2}{R-3/2}\right) + \frac{\hat{k}\Delta r - 2}{(-\hat{k}\Delta r - 2)} \left(\frac{R+1/2}{R-3/2}\right)}{\Delta t} \right]$$

$$= -u_{R-1,n} + u_{R,n} \left[\frac{2\Delta t - 2(\Delta r)^2 \left(\frac{R-1/2}{R-3/2}\right) + \frac{\hat{k}\Delta r - 2}{(-\hat{k}\Delta r - 2)} \left(\frac{R+1/2}{R-3/2}\right)}{\Delta t} \right]$$

$$+ 2 \left(\frac{R+1/2}{R-3/2} \right) \frac{2\Delta r \hat{k}}{(-\hat{k}\Delta r - 2)}$$

At each time level (where $t > 0$) R equations may be written containing R unknowns. Furthermore these equations constitute a tridiagonal matrix. Equations of this form are readily solved for u as a function of r and t by the Thomas algorithm [3]. \square

REVIEW: Multiphase Science

Continued from page 197.

Chapter Four is a review of a reboiler. The authors struck a balance between practical application and scientific analysis by discussing both the design strategy and the appropriate correlations used for thermal-hydraulic analysis. The authors recommend that a set of several design equations be presented and a comparison be made of the relative merit of each for particular design applications.

Chapter Five covers flow of gas-solid mixtures through standpipes and valves. In this chapter, most attention was devoted to the flow regimes of solid-gas in standpipes, which include four basic types: type I fluidized flow and type II fluidized flow, PACFLO and TRANPACFLO, and the combination thereof.

The gas-solid flow in a standpipe is still a subject with incomplete knowledge. The authors made an effort to introduce the subject in a rational manner. The readers can use this review as a good start to understand not only gas-solid flow in standpipes but may also find it inspirational in trying to understand other multi-phase flow systems.

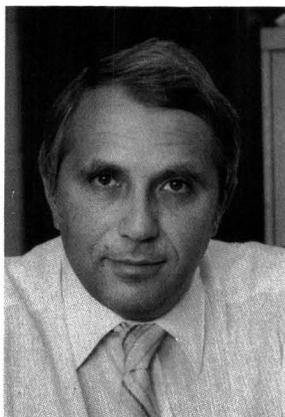
Chapter Six deals with core-annular flow of oil and water through a pipeline. The motivation of such special flow is to find a reduction of pressure drop for pumping heavy, viscous oil through a pipe using water in annular as a "lubricant." Thus, the authors proposed their lubricating-film model. In this model, the main features are the inclusion of core eccentricity and the ripple lubricating film. The validity range of core-velocities for the lubricating-film model was given. The authors also proposed some possible ways of improving the models and predictions. \square

CHEMICAL REACTION ENGINEERING*

Current Status and Future Directions

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CHEMICAL REACTIONS have been used by mankind since time immemorial to produce useful products such as wine, metals, *etc.* Nevertheless, the unifying principles that today we call chemical reaction engineering were not developed until relatively a short time ago. During the decade of the 1940's (not even half a century ago!) a transition was made from descriptive industrial chemistry to the conceptual unification of reaction processes and reactor types. The pioneering work in this area of industrial practice was done by Denbigh [1] in England. Then in 1947, Hougen and Watson [2] published the first textbook in the U.S. that presented a unified approach in tackling catalytic kinetics and reactors. This book has had a lasting effect on the American school of catalytic reaction engineering as focused primarily on petroleum processing. The expansion of the petroleum



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and petrochemical industry provided a fertile ground for further development of reaction engineering concepts. The final cornerstone of this new discipline was laid in 1957 by the First Symposium on Chemical Reaction Engineering [3] which brought together and synthesized the European point of view. The American and European schools of thought were not identical, but in time they converged into the subject matter that we know today as chemical reaction engineering, or CRE. The above chronology led to the establishment of CRE as an accepted discipline over the span of a decade and a half. This does not imply that all the principles important in CRE were discovered then. The foundation for CRE had already been established by the early work of Frank-Kamanteski, Damkohler, Zeldovitch, *etc.*, but at that time they represented "voices in the wilderness," and no coherent area of specialization known as CRE had yet emerged.

What then is CRE? It is the discipline that quantifies the interplay of transport phenomena and kinetics in relating reactor performance to operating conditions and input variables. CRE, in achieving this goal, relies on thermodynamics, kinetics, fluid mechanics, transport phenomena, chemistry or biochemistry, physics, *etc.* The key equation of CRE can be stated as

$$\text{Reactor Performance} = f(\text{input, kinetics, contacting})$$

Product yield, or selectivity, or production rate can be taken as measures of performance. Feed and operating conditions constitute the input variables. Fluid mechanics of single or multiphase flows determines contacting, while kinetic descriptions relate reaction rate to pertinent intensive variables such as concentrations, temperature, pressure, catalyst activity, *etc.*

CRE is a general methodology for approaching any system (chemical, biochemical, biological, *etc.*) where engineering of reactions is needed, *i.e.*, where cause and effect relations imparted by reaction and observed in small laboratory vessels need to be "scaled-up" to large commercial reactors. CRE can then be used by the research engineer to quantify the reaction system and assess transport limitations, by the design engineer in designing the plant reactor, and by the man-

What is CRE? It is the discipline that quantifies the interplay of transport phenomena and kinetics in relating reactor performance to operating conditions and input variables . . . in achieving this goal [it] relies on thermodynamics, kinetics, fluid mechanics, transport phenomena . . . physics, etc.

ufacturing engineer in keeping the reactor running according to specification. The power of CRE is that it spans the domain of many diverse technologies in the petroleum, metallurgical, chemical, materials, fermentation and pharmaceutical industries. The same framework can be used to attack a reaction problem irrespective of its chemical nature.

CURRENT STATUS OF CRE

It is impossible in a brief review to do justice to a discipline as broad as CRE. One can approach the subject from the generic point of view and talk about the status of CRE in dealing with homogeneous gaseous or liquid systems, heterogeneous gas-solid catalytic systems, heterogeneous gas-solid noncatalytic systems, gas-liquid systems, gas-liquid-solid systems, *etc.*, or one can approach it from the technological point of view and consider the status of CRE in hydrodesulfurization of crude oil, biochemical processing, polymerization, food production, baking, electrochemical processing, air pollution abatement, coal gasification, *etc.* All of those areas have received attention, and plenary lectures were dedicated to them at various ISCRE symposia. Here, we will just try to impress upon the reader the current status of teaching CRE at universities and the possible disparity between that activity and industrial practice.

CRE in Academia

It is instructive to note that in 1958, only 18% of the academic departments in the U.S. offered a course on CRE to undergraduate students. In 1962 that percentage had already risen to 53%, and by the end of the 1960's, CRE had become a required course in all accredited departments in the U.S. This has remained unchanged today. In the early years, Hougen and Watson [2] was the only textbook considered in the U.S. It has been replaced mainly by Levenspiel's text [4] in the 1960's. Brotz [5] and Kramers and Westerterp [6] seem to have been the standards in Europe until recently. The number of general textbooks of the subject exceeded forty-eight in 1980 and continues to rise dramatically. These texts have been summarized by Levenspiel [7] and Dudukovic [8]. Specialized monographs treating a particular topic within CRE are also proliferating.

What are the undergraduate students exposed to in a typical CRE course in the U.S.? According to the latest survey [8] (and not much has changed since

then) most of them (over 67%) learn the ideal reactor concepts, deal with evaluation of kinetic data from batch experiments, treat some nonideal reactors (via tanks in series and dispersion model, mainly) and are introduced to mechanisms and kinetics. Only about 60% are introduced to the transport-kinetic interactions in heterogeneous systems, less than 50% deal with realistic packed-bed reactor problems, and fewer than 20% are exposed to fluidized beds. Most departments claim some industrial input into the course, but it consists mainly of the instructor's industrial experience. Use of digital computers, numerical methods, and programming in dealing with realistic design problems is on the rise. While over 55% of the departments utilized numerical approaches in 1982, it is expected that almost all will do so in 1987.

The increased use of computational tools in CRE courses is welcome because it allows the basic CRE principles, once mastered, to be applied to more realistic, practical problems. Quantification of CRE principles, through extensive use of mathematics, dates back to Amundson and co-workers at the University of Minnesota [9] which at the time represented a significant step forward. Today, most graduate courses in CRE suffer to some extent from mathematical oversophistication that has lost touch with reality. For example, students may work on various numerical schemes to solve complex reactor models while assuming that the kinetic relations are known with great accuracy—an unlikely event in industrial practice. A trend toward better understanding of process chemistry or biochemistry, and improved tools to deal with scant and inaccurate data, seem to be needed instead. The "computerization" of the CRE courses allows the students today to handle reactor models that represented doctoral thesis projects a decade ago. Therefore an increased emphasis on tying CRE principles to process chemistry is possible and is needed.

Academic research is split between traditional reactor type oriented research and the new emphasis on process development. For example, continued research is being done on improved understanding of various multiphase reactors such as fluidized beds, slurry reactors, three phase fluidized beds, bubble columns, trickle-beds, stirred tanks, *etc.* Increased emphasis on process oriented research is apparent, *e.g.*, silane pyrolysis to silicon, epitaxial growth of single crystals, preparation of novel zeolites, preparation of new polymers, *etc.*

Industrial Practice of CRE

There is a wide gap between industrial practice and academic approaches to CRE in the U.S. It is expected that the gap is even wider in developing countries. Reaction engineering is practiced at a high level of sophistication, paralleling approaches outlined in most modern textbooks [10-12], only in some large petroleum companies. There, kinetic data are sought in absence of transport effects on small scale equipment, mechanisms and kinetics on catalytic surfaces are studied, and the scale-up problem is approached in stages. Scale-up often involves the evaluation of hydrodynamic assumptions made in reactor design by tracer studies on a cold real scale model of the production reactor. Recently, the Mobil Corporation has used this classical and methodical approach to successfully develop methanol-to-gasoline large scale fluidized bed reactors which were the key to the success of the process. Unfortunately, U.S. petroleum companies have not been building many new plants in the last five years, and their CRE advances have been temporarily halted. In industry, advances of a methodology like CRE are process demand driven. When the demand disappears, the advances slow down. The danger of this situation is that some of the best CRE teams which had been assembled at large petroleum companies are now disintegrating and dispersing. Thus, when synfuels become needed again, there will be a painful period of adjustment in reassembling teams with CRE expertise.

Chemical, pharmaceutical and other companies in the U.S. and elsewhere in the world have not, in general, practiced CRE on the same level as petroleum companies. Often they did not realize that the reactor, although not a major item in capital expenditures for a new plant, by its performance dictates the load on and size of separation equipment. Reactor design often followed a "seat-of-the-pants" approach and was rarely optimized. Major advances have been made in reactor control where digital, multivariable control conducted through a central station is the dominant feature of modern plants. Frequently, companies either rely on patent protection or are pressured to introduce a product on the market within a short time, so they tolerate sloppy reactor design. Prater's principle of optimum sloppiness [13] is not practiced here. That principle, practiced in petroleum companies, states that as more and more relations for a reaction system are quantified, costs go up but the uncertainty of design goes down, and the cross section of the two curves indicates an optimum. Most reactor designs in chemical and other industries are done with very little

quantitative information in hand regarding kinetics. Scale-up based on equal liquid hourly space velocity (LHSV) is the rule of the day, followed by incorporation of additional reactor volume in the design as a safety factor. It is hoped that the increased competitiveness in the specialty chemicals area will force the chemical companies to practice CRE at a higher level. Significant savings should be possible with better reactor designs.

CRE research in industry has been traditionally process driven. New contactors (new reactor types) are introduced for a particular technology and then sometimes become adopted elsewhere, *e.g.*, fluidized bed for catalytic cracking, radial flow reactor for ammonia synthesis, Shell bunker (moving) bed reactor for hydrodesulfurization with deactivating catalysts, fast fluidized bed for coal combustion, *etc.* Most of the industrial research today is oriented towards the development of better zeolites and other catalysts, specialty chemicals, specialty polymers, composite materials, high performance ceramics, improved pigments, *etc.* CRE, unfortunately, seems to play only a minor role in these bench scale endeavors, but is expected to be needed in scale-up. The current economic situation has brought to a temporary halt the research on synthetic fuels, alternate energy sources, and processing of heavy oils.

FUTURE TRENDS

Reaction engineering is now a mature discipline. It evolved in the 1940's from the ideal reactor concepts on one side and from the systematic treatment of transport-kinetic interactions on catalyst particles on the other. Mathematical approaches of the early 1960's established the foundation on which the principles of CRE dealing with transport-kinetic interactions can be applied to a vast variety of fields. The unification of CRE approaches has been achieved. Increased computerization allows its application in complex problems. What of the future then? What will be the research directions and where, *i.e.*, in which field, will the major industrial impact be felt? What kind of CRE should be taught and practiced in developing countries?

Many would argue that the future of CRE is in high technologies. However, high technology must be carefully defined. Often biotechnology, high technology, high performance composites, semiconductor materials, high performance ceramics, optical fibers technology, pharmaceuticals, *etc.*, are understood to be high technology. However, that is not necessarily so. For example, a fully automated modern steel plant

may involve much more sophistication, control, and automation than a primitive autoclave for curing of thermosetting composites or for production of cells. Really, what is often meant by high-tech is high-value added products, *i.e.*, relatively new technologies that produce specialty, often low volume, products the price of which is an order of magnitude above their manufacturing costs! We have no argument with the premise that CRE will be needed and will prosper by advancing high technology products. However, we are not at all convinced that it will play a significant role in development of high-value added products unless they also happen to be high technology products. The reason for this is simple and has nothing to do with science or engineering, but with economics. In producing a high value added product (a miracle drug, a super fast semi-conductor chip, *etc.*) the bottle-neck is in the science. Once a bench scale scientist makes a breakthrough, scale-up factors required are small and the efficiency of manufacturing is not critical since the profit margin is huge. This is the reason why a demand for CRE specialists in biotechnology has so far failed to materialize. Very specific, low-volume products are being sought, and engineering involvement is small and secondary to that of scientists. This will change when competitiveness in this area increases and/or when large scale biomass conversion is attempted.

The CRE research directions in the U.S. invariably follow the funding trends. Therefore in the short-term future (five years) one can expect increased emphasis on

- aerosol reactors in production of ceramics and optical fibers
- batch processing, control and optimization
- biotechnology
- chemical vapor deposition in preparation of semiconductor materials such as MOCVD of gallium arsenide, *etc.*
- combustion and generation of particulates
- reaction engineering of composite materials
- reaction engineering in microgravity
- reaction engineering of specialty polymers
- zeolite catalysts, catalyst preparation and quantification, modifications with transition metals, studies of configurational diffusion.

Over the long run we well know that trends are cyclic in nature. The energy problem has not been solved permanently. Eventually petroleum based products will need replacement and synthetic fuels, renewable energy sources, and new materials will be needed. The currently dormant research on

- coal gasification and liquefaction
- methanol synthesis

- methanol to chemicals conversion
- multiphase reactors
- synfuels from various sources, *etc.*

will be resurrected in addition to the currently popular areas.

All of the above areas seem to be more process oriented than the CRE research in the 1960's and 1970's that concentrated on analysis of various reactor types. The trend of remarrying CRE concepts with process chemistry is probably here to stay. It is of course possible to make further dramatic improvements in our understanding and *a priori* design of various multiphase reactor types that are today designed based on empirical relations. The tools necessary to achieve this are available and consist of improved non-invasive technology for monitoring flow patterns and concentration profiles (gamma cameras and sources, x-ray and positron emission tomography, optical fibers, *etc.*) and of supercomputers that make difficult flow calculations possible. However, it is unlikely that any society will in the present climate allocate the resources necessary to tackle with the best available tools a problem such as fluidized bed or trickle-bed *a priori* design. If these breakthroughs happen, and they are possible based on our currently available arsenal of tools, they will occur in relation to the development of a particular technology that relies on such a reactor type. Research funding will be directed toward the development of new processes for pollution abatement and acid rain elimination, for the development of improved data bases in treatment of hazardous chemicals, for processes for hazardous chemicals elimination, for expert systems for reactor safety, *etc.*

In the near future we can expect chemical reaction engineers to develop a second specialty (a "minor," so to speak) in a scientific discipline such as microbiology, electronics, ceramics, materials, *etc.* Then they will work very effectively together with scientists in the early stages of developing new processes. Capable managers with technical backgrounds will realize that productivity and the success rate in developing new processes can be increased dramatically by letting chemical reaction engineers work with scientists on a new process or new material from the very conception of new ideas. Thus, we will see significant involvement of CRE in new areas such as materials, semiconductors, ceramics, specialty polymers, and food and feed. Major industrial impact will be in scale-up and design of flexible processes that can meet changing customer needs. All high technology areas will benefit from CRE, and they include "old" technologies, large scale commodity and specialty chemicals, petroleum

processing, and all the new high-value products where a high level of competition exists.

This implies that developing countries must teach well the CRE principles, but should not try to do research in all of the areas. Their research should be directed toward improving and further developing the technologies for which there are economic advantages and incentives. A close and productive academic-industrial relationship is the only way for developing nations to achieve a competitive position in certain industries.

Since reaction engineering is considered a mature discipline, it is clear that higher returns are expected by application of the CRE principles in emerging technologies than by further advancement of these principles. It is often argued that traditional approaches in studying a specific reactor type in a general sense bring diminishing returns and incremental improvements in our knowledge base. This might be true if one insists on using old fashioned experimental and mathematical tools. However, as argued earlier, our scientific base in instrumentation and large scale computation has reached a new dimension. If we would bring these new tools to bear on multiphase reactor problems, advances paralleling those in medicine would be possible. At present, the limiting factor is a lack of funds since generic reactor analysis cannot be compared in appeal to health care. Nevertheless, research of various reactor types will continue, with increased emphasis on novel devices that combine reaction and adsorption in one unit (*e.g.*, reactive distillation, chromatographic reactor, supercritical reaction and separation). We should also remember that unexpected breakthroughs are possible at any time and in any area. After all, who could predict the timing of Danckwerts residence time distribution concepts and their impact on CRE that lasted several decades? CRE will remain a vital field and a fun field to do research in and to practice in industry. Steady progress will be made, more science will be brought back to CRE, and major breakthroughs are possible. These are the conclusions of our recent Engineering Foundation Conference on reaction engineering [14].

SUMMARY

Chemical reaction engineering is a mature discipline that has emerged from the treatment of petroleum related catalytic reaction problems and has been broadened to the point that the word chemical should be dropped from its title. Reaction engineering principles deal with the transport phenomena-kinetic

interactions and are general in nature and applicable to all types of processing and all phenomena where, in conversion of raw materials to useful products or to energy, reactions occur. Reaction engineering as a discipline has profited immensely from the availability of increased computational power and from the existence of data base management. Its further evolution is expected to make its dependence on various sciences (chemistry, biochemistry, materials, *etc.*) even stronger and could possibly result in formation of various CRE subdisciplines.

Reaction engineering will continue to prosper in the future by relying more on basic chemistry in reaction pathway development and by incorporating basic hydrodynamic principles in reactor design. Empirical correlations will gradually be replaced by relations based on first principles. In spite of all these predicted specific advances, however, the most valuable resource will remain the reaction engineering methodology itself. Perhaps the ultimate achievement will be the development of expert systems for reaction engineering which will combine the fundamental approaches of science with the experience, instinct and intuition of many great reaction engineers. These systems will then be able to lead us in the design of safe, optimal reactors based on a minimum data set.

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**MULTIPHASE CHEMICAL: REACTORS:
THEORY, DESIGN, SCALE-UP**

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Reviewed by**Y. T. Shah****University of Pittsburgh**

This volume was developed from notes prepared for a short course on the theory, design, and scale-up of multiphase reactors held in 1982. The course was given by a group of researchers in multiphase reactors or in some closely related areas of study.

The first chapter (by A. Gianetto) deals with the classification, characteristics, and uses of these types of reactors. Chapters 2 to 5 (by J. C. Charpentier) are extensive reviews of various aspects of gas-liquid reactors. They cover: mass transfer coupled with chemical reaction (Chap. 2); solubility and diffusivity of gases in liquids (Chap. 3); measurement of gas-liquid parameters (Chap. 4); and simulation of industrial and pilot scale gas-liquid absorbers (Chap. 5). Generally, the term multi-phase reactors implies reactors with more than two phases. The author, at the introduction of Chapter 2, explains the reason for including the gas-liquid (two-phase) system in a monograph devoted to multiphase reactors, on the basis of its similarity with the latter types of systems.

Chapters 6 and 7 (by P. L. Silveston) deal with diffusion and reaction within porous catalysts, and with the structure of the solid phase and its influence on diffusivity. These classical subjects can also be classified under the two-phase category.

Chapters 8 to 12 introduce the core of the book. They treat in detail three phase fixed bed reactors, with special attention paid to trickle-bed reactors. Hydrodynamics (Chap. 8), Mass Transfer (Chap. 9), Solid Wetting (Chap. 10), Heat Transfer (Chap. 11), and Scale-Up of Trickle-Beds (Chap. 12) are developed by H. Hofmann, J. C. Charpentier, J. M. Smith, G. Baldi, and A. Gianetto, respectively. The general evaluation of three-phase reactors is completed with Chapters 13 to 15, where the hydrodynamics and mass transfer in bubble columns (by H. Hofmann), hydrodynamics and gas-liquid mass transfer in stirred slurry reactors (by G. Baldi) and modeling of slurry reactors (by J. M. Smith) are presented.

All through these chapters correlations and models are critically reviewed, with each author developing his subject in his own style. Hofmann presents his chapters in a concise and clear way, with appropriate recommendations whenever possible. Mass transfer in fixed beds, developed by Charpentier, is written with numerous references and correlations of experimental data. Smith presents the wetting factor in trickle-beds and modeling of slurry reactors in two short chapters. Heat transfer in three-phase fixed beds and hydrodynamics and gas-liquid mass transfer in stirred slurry reactors by Baldi, and the scale-up of trickle-bed reactors by Gianetto, are written in a manner that can be easily followed by the reader.

In addition, there are three chapters in which the design and scale-up of multiphase reactors for Hydro-treating (by A. Gianetto and P. L. Silveston), Coal Liquefaction (by P. L. Silveston) and Biological Processes (by M. Moo-Young) are evaluated. In particular, the last chapter puts formally under the framework of multiphase reactors an important area of research not included in previous books about the present subject.

The goal of this monograph, as stated by the editors, is to present the dominant physical processes occurring in the most widely used three-phase reactors, and to provide models for their scale-up. Since there are several authors, the reader faces different styles of presentation as well as some overlapping (claimed unavoidable and even desirable by the editors). Part of the presented material is an enriched version of previous contributions by some of the authors to already published seminars and journal reviews.

The production quality of text could have been improved: there are many typographical errors. Despite being published in 1986, the monograph's references (with a few exceptions) reach only until 1982. The literature in this area grows at such a rapid rate that the book should have come out just after the conference to create its maximum impact. The book will be particularly useful for those researchers who have to deal with multiphase reactors, and who need an overview of the whole area. The monograph provides substantial contributions that will be helpful for those facing this subject for the first time. For those researchers familiar with multiphase reactors, the book provides another set of review that complements the already available excellent monographs in the area. □

COMBUSTION ENGINEERING

Continued from page 199.

aided design methods in U. S. industry, with emphasis on clean and efficient use of low-grade fuels. The approach is to integrate kinetic and mechanistic data, physical/chemical fuel property data, and process performance characteristics into comprehensive state-of-the-art computer models to be used in the simulation, design and optimization of advanced combustion processes. The underlying philosophy is that a fundamental systems approach applied to carefully selected systems will have wide application to many important combustion problems. The products of the new center will include: (1) new computer-aided-design combustion technology, (2) new understanding of combustion mechanisms and their relation to fuel properties, (3) improved process strategies, and (4) students educated in the fundamentals of combustion engineering who can solve a wide range of problems.

Program. Research projects are focused in six fundamental areas: (1) fuels characterization and reaction mechanisms, (2) fuel minerals, fouling and slagging, (3) pollutant formation and control, (4) comprehensive model development, (5) process characteristics/model evaluation, and (6) exploratory areas. The first five areas are the key elements needed for complete design, optimization and control of advanced technology for combustion processes. The following three research subjects, specifically identified by a blue ribbon panel as among the potentially most productive for the near-term, are receiving particular emphasis: (1) comprehensive and generalized modeling of coal combustion processes, (2) identification of the relationships between chemical/physical properties of fuels at the molecular level and reaction processes, and (3) fundamentals of formation and control of sulfur and nitrogen emissions. Exploratory research presently includes hazardous waste disposal and may expand in the future to fluidized beds, catalytic combustion, or catalytic reduction of NO_x . The heart of the center's research program presently consists of about thirteen research projects at BYU and U of U, funded on the basis of excellence and pertinence to the focus/subject areas, as well as eight research projects funded by a consortium of companies through the center. Some of the key investigators involved in some of these projects are listed in Table 4.

INDUSTRIAL RELATIONS AND TECHNOLOGY TRANSFER

The Executive Advisory Council (Table 2), consisting of highly placed executives and professionals, pro-

vides essential direction on the focus of the center's research and academic programs. Besides financial support, the Technical Associates of the center (Table 3) participate through representation in the Technical Review Committee and through attendance at the ACERC Annual Review. Visits and interchanges of students and faculty with industrial professionals of these companies and laboratories are also planned. Center funds will provide half-support for a visiting industrial research fellow on a continuing basis. To promote technology transfer, an annual review and a biannual technical conference are held on campus with presentations on advanced combustion from academia, government and industry. The center also disseminates new information through annual technical reports, journal publications, presentations at meetings, technical workshops, and computer networking.

ACADEMIC PROGRAM

The objective is to educate students in engineering and scientific fundamentals using the systems approach in a way that will prepare them to solve a wide range of problems. Fellowship support is provided for 4-5 graduate and 8-10 undergraduate students. A combination of 3-4 new and 20 currently available courses among six departments in four colleges at the two universities provide a broad basis for both general and specific education in combustion-related science and engineering. At the undergraduate level, students re-

TABLE 4
Key Investigators: ACERC

INVESTIGATOR	AREA OF EXPERTISE
Calvin H. Bartholomew, ChE, BYU William C. Hecker, Chem. Eng., BYU	Catalysis, Surface properties of coal and chars
David M. Grant, Chemistry, U of U Ronald J. Pugmire, Fuels Eng., U of U	NMR characterization of fuels
George Hill, Chem. Eng., U of U Henk Meuzelaar, Biomaterials Profiling Center, U of U	Coal characterization and properties correlation
Milton R. Lee, Chemistry, BYU	Chromatographic analysis of fuels
Angus Blackham, Chemistry, BYU John W. Cannon, Mech. Eng, BYU	Fouling, slagging, minerals, chemical analysis
David W. Pershing, Chem. Eng., U of U	Pollutant formation and sub-models
Philip J. Smith, Chem. Eng., BYU L. Douglas Smoot, Chem. Eng. BYU	Comprehensive model development
Mike Stephensen, Civil Eng., BYU	Graphics code development
Paul O. Hedman, Chem. Eng., BYU Geoffery Germane, Mech. Eng., BYU	Process characteristics and diagnostics

ceive general exposure to systems, energy, and environmental engineering in the form of senior electives; a new undergraduate program option will be established in chemical engineering at BYU. Graduate students receive a more specific education in such topics as combustion science and engineering, kinetics, physical and chemical structure of solids and fuels, and process modeling and control. Selected courses, seminars, and ad hoc seminars from visiting industrial lecturers at both universities are offered to students in a coordinated curriculum. Efforts are being made to optimize the use of remote circuit TV and a shuttlebus system between the two campuses. Graduate and undergraduate participation in combustion research is also stimulated by research fellowships and assistantships. A continuing education program is being organized to serve the needs of industrial engineers and scientists for professional development in combustion related subjects and to train them in the use of simulation codes using state-of-the-art computer graphics workstations in our new Computations Center.

MAJOR ACCOMPLISHMENTS OF THE FIRST YEAR

During the first year of its existence, the center initiated and funded thirteen new projects, purchased a new Convex Mini Supercomputer, and completed construction of a new computations laboratory that features state-of-the-art work stations for computer code development and demonstration. A proposal for a link to the NSF-supported San Diego Cray for running these codes was submitted to NSF and accepted. Workshops on comprehensive modeling, fouling and slagging, and other advanced combustion topics were conducted; organizational meetings for ACERC faculty, the Executive Advisory Council, and the Technical Review Committee were held; working groups involving prominent scientists and engineers in each of the thrust areas were organized; visits were made to other cooperating laboratories, including Sandia National Laboratories, for purposes of establishing collaboration; and a number of prominent engineers and scientists were invited to lecture in the center.

Significant progress was made on twenty-one research projects in the six thrust areas of research presently emphasized in the center. These projects included eight active research projects funded by the foundational consortium grant. A summary of the accomplishments of the ACERC and consortium projects can be obtained from the author. Consortium projects were active for the entire fiscal year, while

ACERC projects were generally initiated in September, 1986, and progress thus covers only an eight month period. Even so, several important accomplishments are noted. Of particular significance was the development and demonstration of a 3-D combustion code for non-reacting, gaseous flows. Work on a significantly improved radiation submodel was successfully completed, while submodel elements for SO_x -sorbent capture, fouling-slagging and carbon nonequilibrium were identified. Further evaluation was completed on an NO_x submodel and a comprehensive 2-D combustion code (PCGC-2) previously developed in the combustion laboratory. A new algorithm for graphical representation of combustion model predictions was developed. Standard ACERC coals were identified, and significant progress was made in characterizing and documenting the physical, chemical and structural properties of several of these coals. Facilities were designed and/or under construction for study of coal devolatilization, char oxidation, and in situ CARS study of flames. Development of submodels and collection of experimental data for SO_x removal and hazardous waste combustion were also initiated. Advanced chromatographic methods were developed for separation of and structural assignment to hydrocarbon fragments from coal extracts of six ACERC coals. Time-resolved Curie-point pyrolysis mass spectrometer studies of a Pittsburgh #8 coal revealed an aromatic distillable fraction, a long chain aliphatic hydrocarbon fraction showing thermoplastic degradation characteristics and a vitrinite-like phenolic fraction exhibiting thermosetting degradation behavior. A new solid state nuclear magnetic resonance spectroscopy technique was developed for aromatic ring structural analysis in coals.

Other accomplishments through the spring of 1987 included the hiring of center secretarial and administrative staff, design and production of a brochure, publication of internal and external newsletters, design and initial construction of new laboratories, and a campaign to increase industrial funding/participation. An educational (academic) program was organized to include new coursework, options, and fellowship programs in combustion-related areas at the two universities. An annual review meeting was held March 5-6, 1987, at BYU involving over one hundred participants from industry, government, academia, and the center. The initial response to the progress during the first year was generally enthusiastic. Thus, it appears that ACERC is off to a good start while combustion research is "heating up" at the BYU and the U of U campuses. □

REVIEW: Injection Molding

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plains the methodology of process control. This chapter bears some similarity to Chapter Three, but is much more thorough and useful.

The last section (Part III) is concerned with data bases and contains Chapter Twelve. It is one of the more useful chapters in the book as it describes the importance to the designer of having data banks available containing the physical properties in both the solid and molten phases of each thermoplastic. This data should be readily available in both the part design and process simulation phases and must be stored in the computer system. The chapter contains an overview of the development of the present data bases, including the types of data available in present systems and future trends.

In summary, there are a number of useful chapters in the book, but unfortunately the connection between chapters is not readily apparent. For the inexperienced engineer, it would be difficult to assemble the appropriate knowledge from this book and then apply it to process control or mold design. The book would be more useful if a section on principles of injection molding, including the fluid mechanics of mold filling and its connection to the properties of a part, were included at the beginning of the book. □

TRANSPORT PHENOMENA

Continued from page 177.

pleted these courses they will know what to look for when they encounter new problems, and they will have acquired the tools necessary to solve a great many of them.

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MICROGRAVITY

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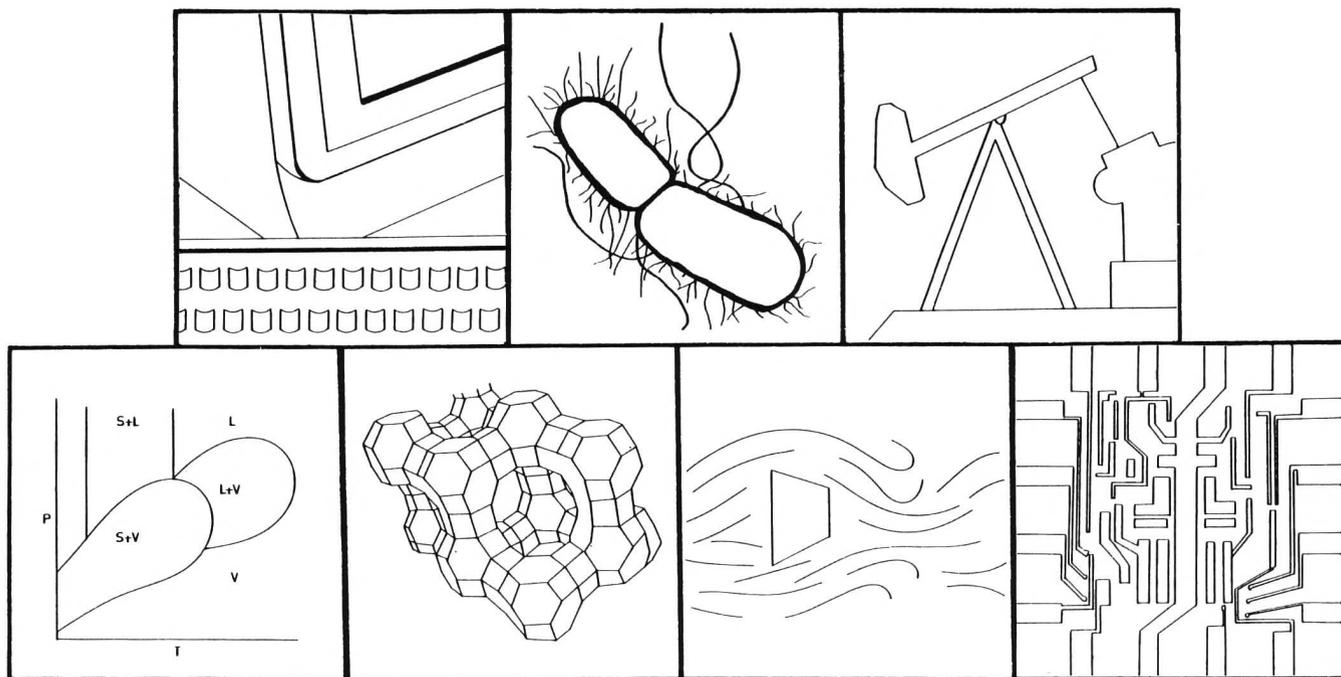
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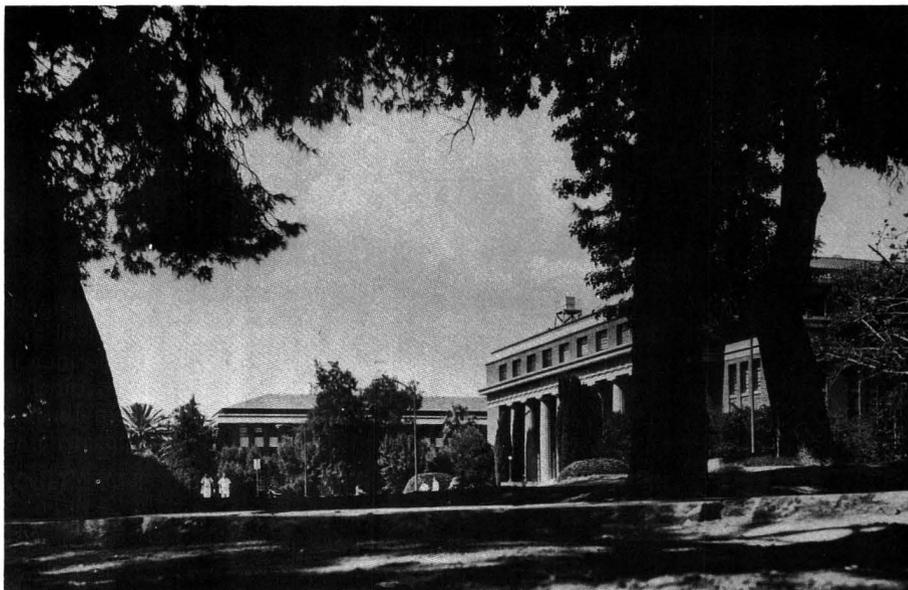
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Nuclear Engineering*
- Thomas O. Spicer** (Ph.D., U. of Arkansas)
*Computer Simulation, Dense Gas
Dispersion*
- Charles Springer** (Ph.D., U. of Iowa)
Mass Transfer, Diffusional Processes
- Charles M. Thatcher** (Ph.D., U. of Michigan)
*Mathematical Modeling, Computer
Simulation*
- Jim L. Turpin** (Ph.D., U. of Oklahoma)
*Fluid Mechanics, Biomass Conversion,
Process Design*
- J. Reed Welker** (Ph.D., U. of Oklahoma)
*Risk Analysis, Fire and Explosion
Behavior and Control*

FOR FURTHER DETAILS CONTACT:

Dr. James L. Gaddy, Professor and Head
Department of Chemical Engineering
3202 Bell Engineering Center
University of Arkansas
Fayetteville AR 72701

LOCATION

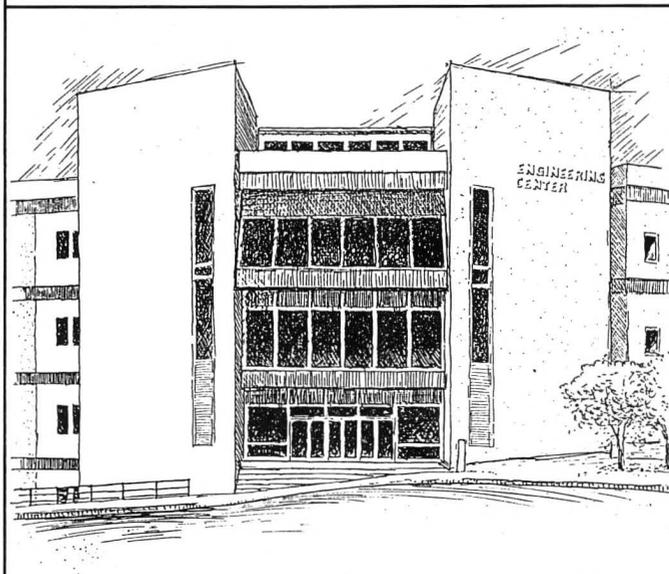
The University of Arkansas at Fayetteville, the flagship campus in the six-campus system, is situated in the heart of the Ozark Mountains and offers students a unique blend of urban and rural environments. Fayetteville is literally surrounded by some of the most outstanding outdoor recreation facilities in the nation, but it is also a dynamic city and serves as the center of trade, government, and finance for the region. The city and University offer a wealth of cultural and intellectual events.

FINANCIAL AID

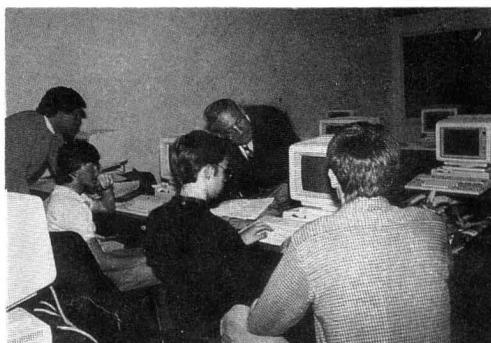
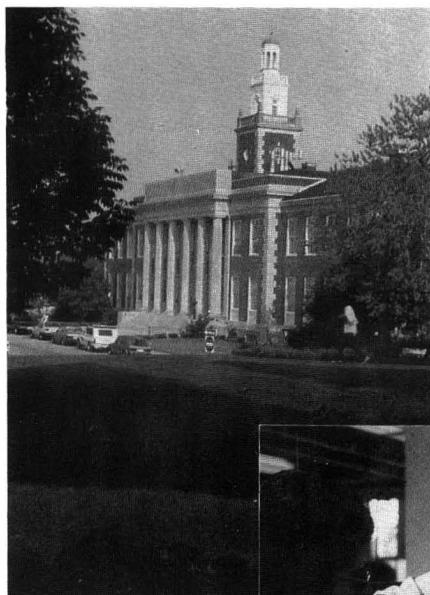
Graduate students are supported by fellowships and research or teaching assistantships.

FACILITIES

The Department of Chemical Engineering occupies more than 40,000 sq. ft. in the Bell Engineering Center, a \$30-million state-of-the-art facility that opened in January, 1987, and an additional 20,000 sq. ft. of laboratories at the Engineering Experiment Station.



CHEMICAL ENGINEERING Graduate Studies



Auburn University

Auburn **æ**
Engineering

THE FACULTY

R. T. K. BAKER (University of Wales, 1966)
R. P. CHAMBERS (University of California, 1965)
C. W. CURTIS (Florida State University, 1976)
J. A. GUIN (University of Texas, 1970)
L. J. HIRTH (University of Texas, 1958)
A. KRISHNAGOPALAN (University of Maine, 1976)
Y. Y. LEE (Iowa State University, 1972)
R. D. NEUMAN (Inst. Paper Chemistry, 1973)
T. D. PLACEK (University of Kentucky, 1978)
C. W. ROOS (Washington University, 1951)
A. R. TARRER (Purdue University, 1973)
B. J. TATARCHUK (University of Wisconsin, 1981)

FOR INFORMATION AND APPLICATION, WRITE

Dr. R. P. Chambers, Head
Chemical Engineering
Auburn University, AL 36849

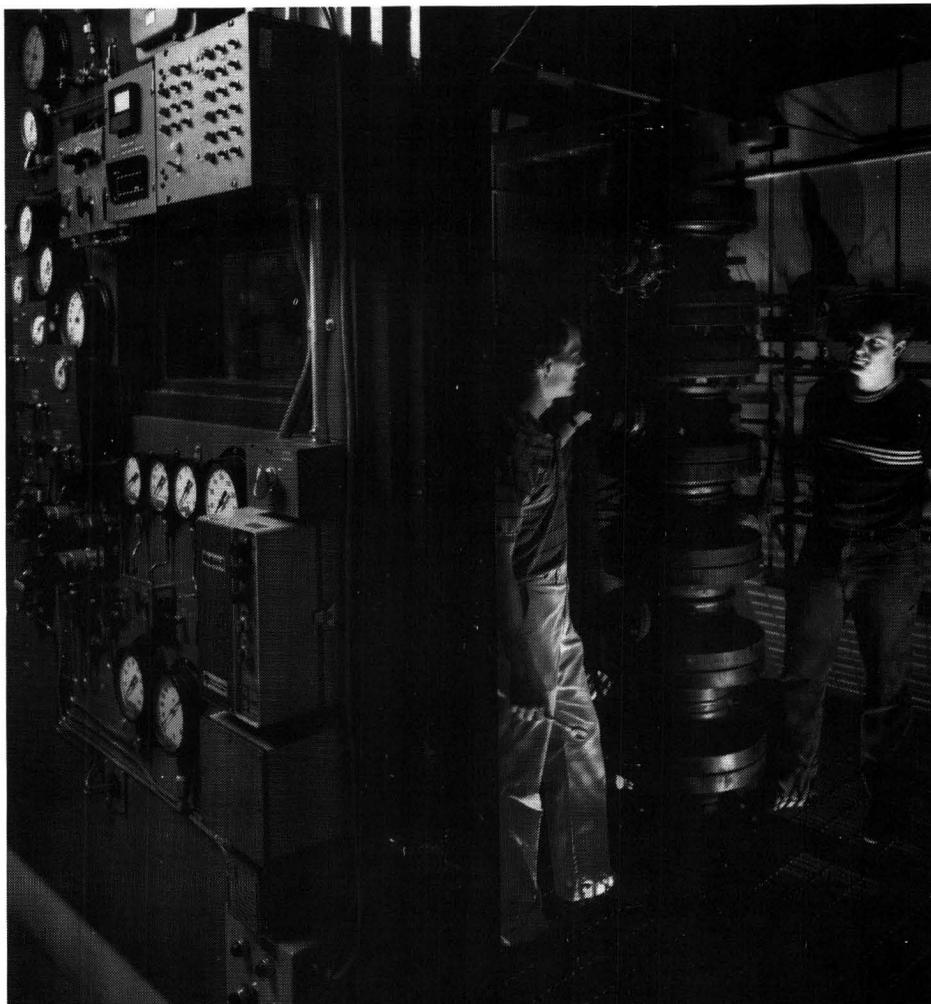
Auburn University is an Equal Opportunity Educational Institution

RESEARCH AREAS

Biomedical/Biochemical Engineering	Oil Processing
Biomass Conversion	Process Design and Control
Carbon Fibers and Composites	Process Simulation
Coal Conversion	Pulp and Paper Engineering
Controlled Atmosphere	Reaction Engineering
Electron Microscopy	Reaction Kinetics
Environmental Pollution	Separations
Heterogeneous Catalysis	Surface Science
Interfacial Phenomena	Thermodynamics
Microelectronics	Transport Phenomena

THE PROGRAM

The Department is one of the fastest growing in the Southeast and offers degrees at the M.S. and Ph.D. levels. Research emphasizes both experimental and theoretical work in areas of national interest, with modern research equipment available for most all types of studies. Generous financial assistance is available to qualified students.



Graduate Studies in Chemical Engineering at Brigham Young University, Provo, Utah

*Programs of study leading to the M.E., M.S. and Ph.D. degrees on a
beautiful campus located at the base of the Rocky Mountains.*

Faculty

Calvin H. Bartholomew, *Stanford, 1972*
Merrill W. Beckstead, *U. of Utah, 1965*
Douglas N. Bennion, *Berkeley, 1964*
James J. Christensen, *Carnegie Mellon, 1957*
Richard W. Hanks, *U. of Utah, 1960*
John N. Harb, *U. of Illinois, 1987*
William C. Hecker, *Berkeley, 1982*
Paul O. Hedman, *BYU, 1973*
John L. Oscarson, *U. of Michigan, 1982*
William G. Pitt, *U. of Wisconsin, 1987*
Richard L. Rowley, *Michigan State, 1978*
Philip J. Smith, *BYU, 1979*
L. Douglas Smoot, *U. of Washington, 1960*
Kenneth A. Solen, *U. of Wisconsin, 1974*

For additional information and application, write:

Graduate Coordinator
Department of Chemical Engineering
350 CB
Brigham Young University
Provo, Utah 84602

Research Areas

Thermodynamics
Transport Phenomena
Calorimetry
Computer Simulation
Coal Combustion and Gasification
Kinetics and Catalysis
Biomedical Engineering
Fluid Mechanics
Chemical Propulsion
Mathematical Modeling
Electrochemistry
Membrane Transport
Nonequilibrium Thermodynamics
Process Design and Control

GRADUATE STUDIES IN CHEMICAL AND PETROLEUM ENGINEERING

The Department offers programs leading to the M.Sc. and Ph.D. degrees (full-time) and the M. Eng. degree (part-time) in the following areas:

- Thermodynamics—Phase Equilibria
- Heat Transfer and Cryogenics
- Catalysis, Reaction Kinetics and Combustion
- Multiphase Flow in Pipelines
- Fluid Bed Reaction Systems
- Environmental Engineering
- Petroleum Engineering and Reservoir Simulation
- Enhanced Oil Recovery
- In-Situ Recovery of Bitumen and Heavy Oils
- Natural Gas Processing and Gas Hydrates
- Computer Simulation of Separation Processes
- Computer Control and Optimization of Engineering and Bio Processes
- Biotechnology and Biorheology

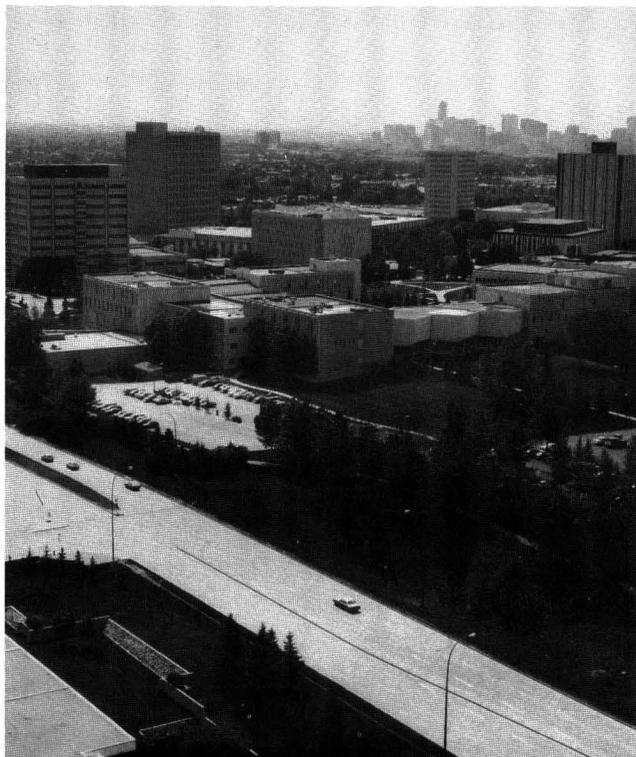
Fellowships and Research Assistantships are available to qualified applicants.

FACULTY

R. A. HEIDEMANN,*	Head (Wash. U.)
A. BADAKHSHAN	(Birm. U.K.)
L. A. BEHIE	(W. Ont.)
D. W. BENNION**	(Penn. State)
F. BERRUTI	(Waterloo)
P. R. BISHNOI	(Alberta)
R. M. BUTLER	(Imp. Coll. U.K.)
M. FOGARASI**	(Alberta)
M. A. HASTAOGLU	(SUNY-Buffalo)
J. HAVLENA	(Czech.)
A. A. JEJE*	(MIT)
N. E. KALOGERAKIS	(Toronto)
A. K. MEHROTRA	(Calgary)
M. F. MOHTADI	(Birm. U.K.)
R. G. MOORE	(Alberta)
P. M. SIGMUND*	(Texas)
J. STANISLAV	(Prague)
W. Y. SVRCEK	(Alberta)
E. L. TOLLEFSON*	(Toronto)
M. A. TREBBLE	(Calgary)

*On sabbatical leave during the 1987-88 academic year.

**Emeritus



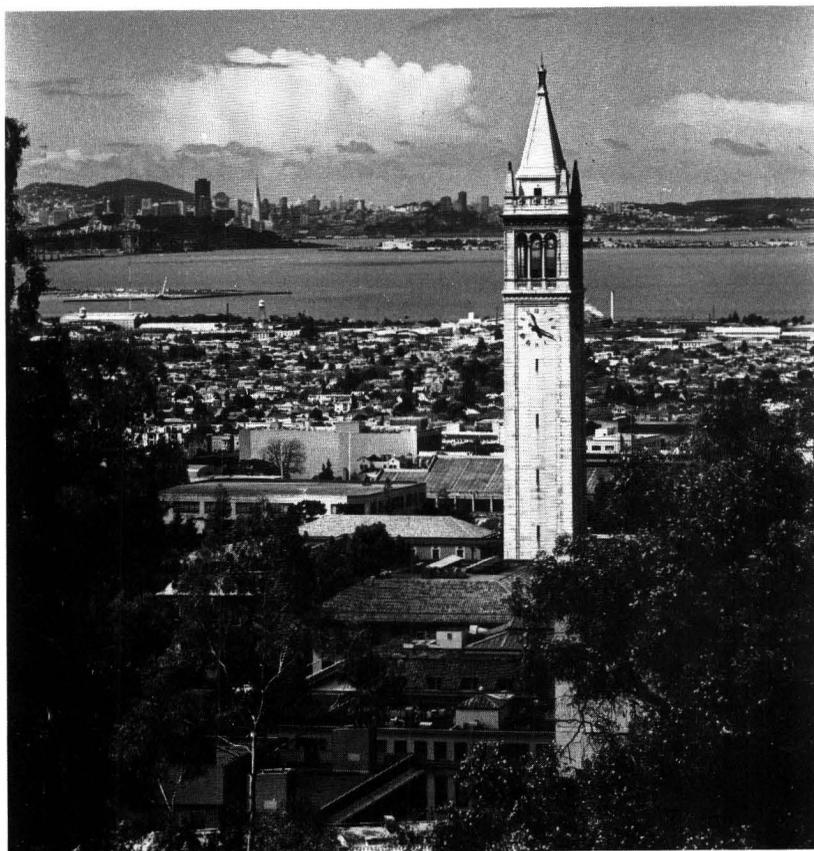
The University is located in the City of Calgary, the oil capital of Canada, the home of the world famous Calgary Stampede and the 1988 Winter Olympics. The city combines the traditions of the Old West with the sophistication of a modern urban centre. Beautiful Banff National Park is 110 km west of the City and the ski resorts of the Banff, Lake Louise and Kananaskis areas are readily accessible.

FOR ADDITIONAL INFORMATION WRITE

**Dr. P. R. Bishnoi, Crairman
Graduate Studies Committee
Dept. of Chemical & Petroleum Eng.
The University of Calgary
Calgary, Alberta T2N 1N4 Canada**

THE UNIVERSITY OF CALIFORNIA,

BERKELEY...



... offers graduate programs leading to the Master of Science and Doctor of Philosophy. Both programs involve joint faculty-student research as well as courses and seminars within and outside the department. Students have the opportunity to take part in the many cultural offerings of the San Francisco Bay Area, and the recreational activities of California's northern coast and mountains.

RESEARCH INTERESTS

ENERGY UTILIZATION
ENVIRONMENTAL PROTECTION
KINETICS AND CATALYSIS
THERMODYNAMICS
POLYMER TECHNOLOGY
ELECTROCHEMICAL ENGINEERING
PROCESS DESIGN AND DEVELOPMENT
SURFACE AND COLLOID SCIENCE
BIOCHEMICAL ENGINEERING
SEPARATION PROCESSES
FLUID MECHANICS AND RHEOLOGY
ELECTRONIC MATERIALS PROCESSING

FACULTY

Alexis T. Bell (Chairman)
Harvey W. Blanch
Elton J. Cairns
Douglas S. Clark
Morton M. Denn
Alan S. Foss
Simon L. Goren
David B. Graves
Donald N. Hanson
Dennis W. Hess
C. Judson King
Scott Lynn
James N. Michaels
John S. Newman
Eugene E. Petersen
John M. Prausnitz
Clayton J. Radke
Jeffrey A. Reimer
David S. Soane
Doros N. Theodorou
Charles W. Tobias
Michael C. Williams

PLEASE WRITE:

Department of Chemical Engineering
UNIVERSITY OF CALIFORNIA
Berkeley, California 94720

UNIVERSITY OF CALIFORNIA-DAVIS



Program

UC Davis, with 20,000 students, is one of the major campuses of the University of California system and has developed great strength in many areas of the biological and physical sciences. The Department of Chemical Engineering emphasizes research and a program of fundamental graduate courses in a wide variety of fields of interest to chemical engineers. In addition, the department can draw upon the expertise of faculty in other areas in order to design individual programs to meet the specific interests and needs of a student, even at the M.S. level. This is done routinely in the areas of environmental engineering, food engineering, biochemical engineering, electrical and computer engineering, and biomedical engineering.

Excellent laboratories, computation center and electronic and mechanical shop facilities are available. Fellowships, Teaching Assistantships and Research Assistantships (all providing additional summer support if desired) are available to qualified applicants.

Degrees Offered

Master of Science
Doctor of Philosophy

Faculty and Research Areas

RICHARD L. BELL, University of Washington
Mass Transfer, Biomedical Applications
ROGER B. BOULTON, University of Melbourne
Enology, Fermentation, Filtration, Process Control
BRIAN G. HIGGINS, University of Minnesota
Fluid Mechanics of Thin Film Coating, Interfacial Phenomena
ALAN P. JACKMAN, University of Minnesota
Environmental Engineering, Transport Phenomena
DAVID F. KATZ, University of California
Biomedical Engineering, Biorheology, Reproductive Biology
BEN J. McCOY, University of Minnesota
Separation and Transport Processes, Kinetics

KAREN A. McDONALD, University of Maryland
Process Control, Biochemical Engineering
AHMET N. PALAZOGLU,, Rensselaer Polytechnic Institute
Process Design and Process Control
ROBERT L. POWELL, The Johns Hopkins University
Rheology, Fluid Mechanics, Acoustics, Hazardous Waste
DEWEY D. Y. RYU, Massachusetts Inst. of Technology
Biochemical Engineering, Fermentation
JOE M. SMITH, Massachusetts Institute of Technology
Applied Kinetics and Reactor Design
PIETER STROEVE, Massachusetts Institute of Technology
Mass Transfer, Colloids, Biotechnology, Thin Film Technology
STEPHEN WHITAKER, University of Delaware
Fluid Mechanics, Interfacial Phenomena, Transport Processes in Porous Media

Course Areas

Applied Kinetics and Reactor Design
Applied Mathematics
Biomedical Engineering
Biotechnology
Colloid and Interface Processes
Fluid Mechanics
Heat Transfer
Mass Transfer
Process Control
Process Design
Rheology
Semiconductor Device Fabrication
Separation Processes
Thermodynamics
Transport Processes in Porous Media

Davis and Vicinity

The campus is a 20-minute drive from Sacramento and just over an hour away from the San Francisco Bay area. Outdoor sports enthusiasts can enjoy water sports at nearby Lake Berryessa, skiing and other alpine activities in the Sierra (2 hours from Davis). These recreational opportunities combine with the friendly informal spirit of the Davis campus to make it a pleasant place in which to live and study.

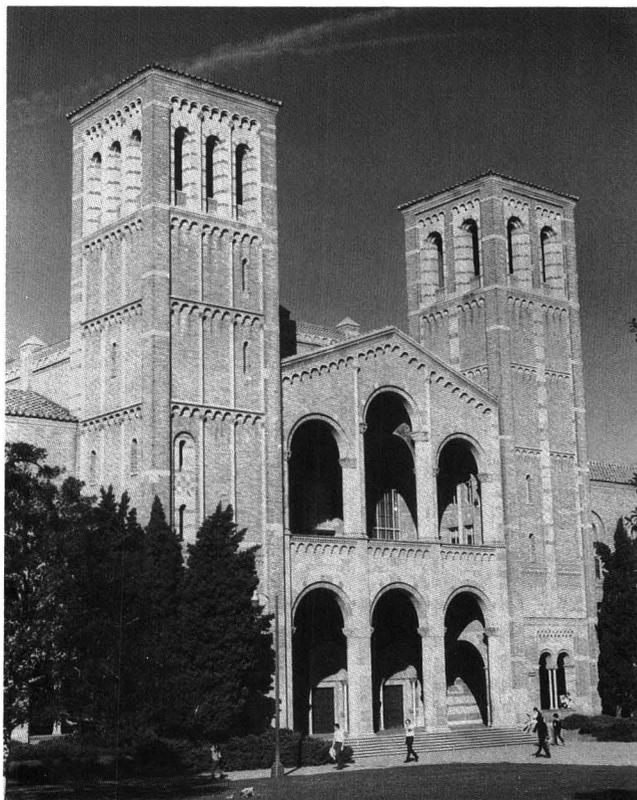
Married student housing, at reasonable cost, is located on campus. Both furnished and unfurnished one- and two-bedroom apartments are available. The town of Davis (population 42,000) is adjacent to the campus, and within easy walking or cycling distance.

For further details on graduate study at Davis, please write to:

**Professor Pieter Stroeve
Chemical Engineering Department
University of California
Davis, California 95616
or call (916) 752-2504**

CHEMICAL ENGINEERING AT

UCLA



PROGRAMS

UCLA's Chemical Engineering Department offers a program of teaching and research linking fundamental engineering science and industrial needs. The department's national leadership is demonstrated by the newly established Engineering Research Center for Hazardous Substance Control. This center of advanced technology is complemented by existing center programs in Medical Engineering and Environmental Transport Research.

Fellowships are available for outstanding applicants. A fellowship includes a waiver of tuition and fees plus a stipend.

Located five miles from the Pacific Coast, UCLA's expansive 417 acre campus extends from Bel Air to Westwood Village. Students have access to the highly regarded science programs and to a variety of experiences in theatre, music, art and sports on campus.

● **FACULTY** ●

D.T. Allen
Y. Cohen
T.H.K. Frederking
S.K. Friedlander
R.F. Hicks
E.L. Knuth
V. Manousiouthakis

H.G. Monbouquette
K. Nobe
L.B. Robinson
O.I. Smith
V.L. Vilker
A.R. Wazzan
F.E. Yates

● **RESEARCH AREAS** ●

Thermodynamics and Cryogenics
Process Design and Process Control
Polymer Processing and Rheology
Mass Transfer and Fluid Mechanics
Kinetics, Combustion and Catalysis
Semiconductor Device Chemistry and Surface Science
Electrochemistry and Corrosion
Biochemical and Biomedical Engineering
Particle Technology
Environmental Engineering

● **CONTACT** ●

Admissions Officer
Chemical Engineering Department
5531 Boelter Hall
UCLA
Los Angeles, CA 90024-1592
(213) 825-9063

UNIVERSITY OF CALIFORNIA

SANTA BARBARA



FACULTY AND RESEARCH INTERESTS

SANJOY BANERJEE Ph.D. (Waterloo)
(Chairman)
Two-Phase Flow, Chemical & Nuclear
Safety, Computational Fluid Dynamics,
Turbulence.

PRAMOD AGRAWAL Ph.D. (Purdue)
Biochemical Engineering, Fermentation
Science

HENRI FENECH Ph.D. (M.I.T.)
Nuclear Systems Design and Safety,
Nuclear Fuel Cycles, Two-Phase Flow,
Heat Transfer.

OWEN T. HANNA Ph.D. (Purdue)
Theoretical Methods, Chemical Reactor
Analysis, Transport Phenomena.

SHINICHI ICHIKAWA Ph.D. (Stanford)
Adsorption and Heterogeneous
Catalysis

JACOB ISRAELACHVILI Ph.D.
(Cambridge)
Surface and Interfacial Phenomenon,
Adhesion, Colloidal Systems, Surface
Forces.

GLENN E. LUCAS Ph.D. (M.I.T.)
Radiation Damage, Mechanics of
Materials.

DUNCAN A. MELLICHAMP Ph.D.
(Purdue)
Computer Control, Process
Dynamics, Real-Time Computing.

JOHN E. MYERS Ph.D. (Michigan)
Boiling Heat Transfer.

G. ROBERT ODETTE Ph.D. (M.I.T.)
Radiation Effects in Solids, Energy
Related Materials Development.

DALE S. PEARSON Ph.D. (Northwestern)
Polymer Rheology

PHILIP ALAN PINCUS Ph.D. (U.C.
Berkeley)
Theory of Surfactant Aggregates,
Colloid Systems.

A. EDWARD PROFIO Ph.D. (M.I.T.)
Bionuclear Engineering, Fusion Reactors,
Radiation Transport Analyses.

ROBERT G. RINKER Ph.D. (Caltech)
Chemical Reactor Design, Catalysis,
Energy Conversion, Air Pollution.

ORVILLE C. SANDALL Ph.D. (U.C.
Berkeley) (Vice Chairman)
Transport Phenomena, Separation
Processes.

DALE E. SEBORG Ph.D. (Princeton)
Process Control, Computer Control,
Process Identification.

T. G. THEOFANOUS Ph.D. (Minnesota)
Nuclear and Chemical Plant Safety,
Multiphase Flow, Thermohydraulics.

JOSEPH A. N. ZASADZINSKI Ph.D.
(Minnesota)
Surface and Interfacial Phenomenon,
Structure of Microemulsions.

PROGRAMS AND FINANCIAL SUPPORT

The Department offers M.S. and Ph.D. degree programs. Financial aid, including fellowships, teaching assistantships, and research assistantships, is available. Some awards provide limited moving expenses.

THE UNIVERSITY

One of the world's few seashore campuses, UCSB is located on the Pacific Coast 100 miles northwest of Los Angeles and 330 miles south of San Francisco. The student enrollment is over 16,000. The metropolitan Santa Barbara area has over 150,000 residents and is famous for its mild, even climate.

For additional information and applications, write to:

Professor Sanjoy Banerjee, Chairman
Department of Chemical & Nuclear
Engineering
University of California,
Santa Barbara, CA 93106

CHEMICAL ENGINEERING
at the
CALIFORNIA INSTITUTE OF TECHNOLOGY

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FACULTY

Frances H. Arnold
James E. Bailey
John F. Brady
George R. Gavalas
L. Gary Leal
Manfred Morari
C. Dwight Prater (Visiting)
John H. Seinfeld
Fred H. Shair
Nicholas W. Tschoegl (Emeritus)
W. Henry Weinberg

RESEARCH INTERESTS

Aerosol Science
Applied Mathematics
Atmospheric Chemistry and Physics
Biocatalysis and Bioreactor Engineering
Bioseparation
Catalysis
Combustion
Colloid Physics
Computational Hydrodynamics
Fluid Mechanics
Materials Processing
Process Control and Synthesis
Protein Engineering
Polymer Physics
*Statistical Mechanics of Heterogeneous
Systems*
Surface Science



for further information, write:

Professor L. Gary Leal
Department of Chemical Engineering
California Institute of Technology
Pasadena, California 91125

It's Your Move.



Department of Chemical Engineering

**Carnegie
Mellon**

John L. Anderson
Membrane and Colloid Transport Phenomena

Lorenz T. Biegler
Process Simulation and Optimization

Ethel Z. Casassa
Colloids and Polymers

Michael M. Domach
Biochemical Engineering

Paul L. Frattoni
Colloid Dynamics Using Optical Methods

Ignacio E. Grossmann
Process Synthesis and Optimization

Rakesh K. Jain
Biomedical Engineering, Tumor Microcirculation

Myung S. Jhon
Polymer Science and Engineering

Edmond I. Ko
Catalysis and Solid State Chemistry

Kun Li
Gas-Solid Reaction Kinetics

Gregory J. McRae
Mathematical Modeling and
Environmental Engineering

Gary J. Powers
Process Synthesis and Design

Dennis C. Prieve
Transport Phenomena in Colloids

Paul J. Sides
Electrochemical Engineering and
Semiconductor Processing

Herbert L. Toor
Heat and Mass Transfer

Arthur W. Westerberg
Design Research

Photo by Ken Andreyo

Study Chemical Engineering at one of the nation's top chemical engineering research facilities...

Case Western Reserve University

Faculty and specializations:

Robert J. Adler

*Ph.D. 1959, Lehigh University
Particle separations, mixing, acid gas recovery*

John C. Angus

*Ph.D. 1960, University of Michigan
Redox equilibria, thin carbon films, modulated electroplating*

Coleman B. Brosilow

*Ph.D. 1962, Polytechnic Institute of Brooklyn
Adaptive inferential control, multi-variable control,
coordination algorithms*

Robert V. Edwards

*Ph.D. 1968, Johns Hopkins University
Laser anemometry, mathematical modelling, data acquisition*

Donald L. Feke

*Ph.D. 1981, Princeton University
Colloidal phenomena, ceramic dispersions,
fine-particle processing*

Nelson C. Gardner

*Ph.D. 1966, Iowa State University
High-gravity separations, sulfur removal processes*

Uziel Landau

*Ph.D. 1975, University of California (Berkeley)
Electrochemical engineering, current distributions,
electrodeposition*

Chung-Chiun Li

*Ph.D. 1968, Case Western Reserve University
Electrochemical sensors, electrochemical synthesis, electrochemistry related to electronic materials*

J. Adin Mann, Jr.

*Ph.D. 1962, Iowa State University
Surface phenomena, interfacial dynamics, light scattering*

Syed Qutubuddin

*Ph.D. 1983, Carnegie-Mellon University
Surfactant systems, metal extraction, enhanced oil recovery*

Robert F. Savinell

*Ph.D. 1977, University of Pittsburgh
Electrochemical engineering, reactor design, and simulation;
electrode processes*

Specializations in:

- Electrochemical engineering
- Laser applications
- Mixing and separations
- Process control
- Surfaces and colloids



CASE WESTERN RESERVE UNIVERSITY
CLEVELAND, OHIO 44106

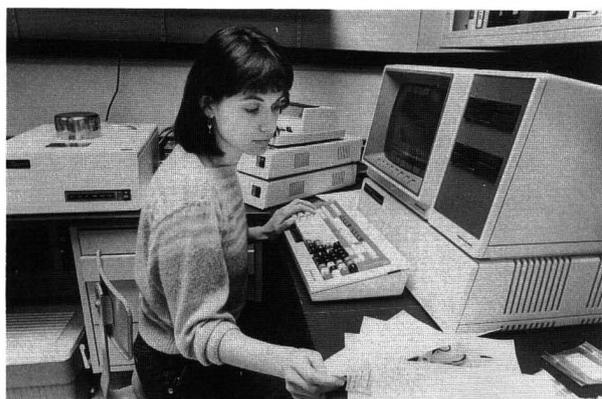
For more information contact:

Graduate Coordinator
Department of Chemical Engineering
Case Western Reserve University
Cleveland, Ohio 44106

The
**UNIVERSITY
OF
CINCINNATI**



**GRADUATE STUDY in
Chemical Engineering
M.S. and Ph.D. Degrees**



FACULTY

Robert Delcamp
Joel Fried
Stevin Gehrke
Rakesh Govind
David Greenberg
Daniel Hershey
Sun-Tak Hwang
Yuen-Koh Kao
Soon-Jai Khang
Sotiris Pratsinis
Neville Pinto
Stephen Thiel
Joel Weisman

CHEMICAL REACTION ENGINEERING AND HETEROGENEOUS CATALYSIS

Modeling and design of chemical reactors. Deactivating catalysts. Flow pattern and mixing in chemical equipment. Laser induced effects.

PROCESS SYNTHESIS

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POLYMERS

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AIR POLLUTION

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COAL RESEARCH

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TWO-PHASE FLOW

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MEMBRANE SEPARATIONS

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FOR ADMISSION INFORMATION

Chairman, Graduate Studies Committee
Chemical & Nuclear Engineering, #171
University of Cincinnati
Cincinnati, OH 45221



M.S. and Ph.D. programs Friendly atmosphere Vigorous research programs supported by government and industry Proximity to Montreal and Ottawa Skiing, canoeing, mountain climbing and other recreation in the Adirondacks Variety of cultural activities with two liberal arts colleges nearby Twenty faculty working on a broad spectrum of chemical engineering research problems

Research Areas include:

Chemical kinetics Colloidal and interfacial phenomena Computer aided design Crystallization Electrochemical engineering and corrosion Integrated circuit fabrication Laser-matter interaction Mass transfer Materials processing in space Optimization Particle separations Phase transformations and equilibria Polymer rheology and processing Process control Turbulent flows And more . . .

Clarkson

Financial aid available in the form of:

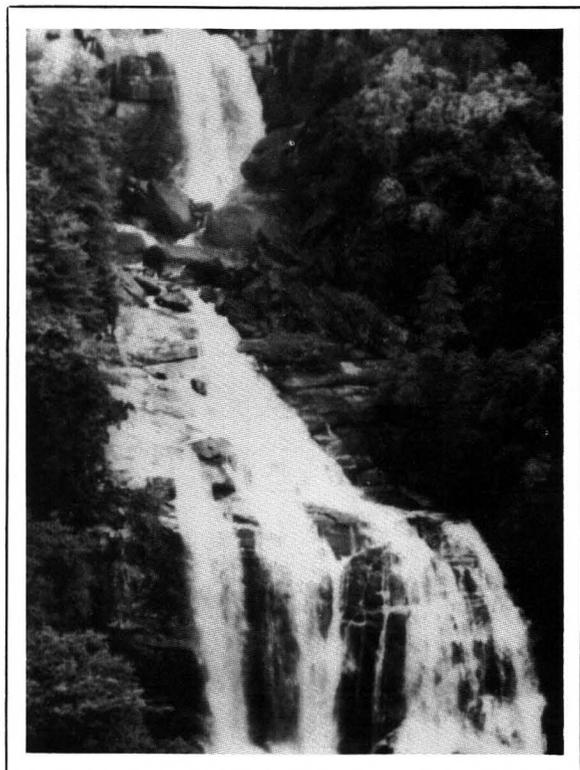
instructorships fellowships research assistantships teaching assistantships industrial co-op positions

For more details, please write to:

**Dean of the Graduate School
Clarkson University
Potsdam, New York 13676**

Graduate Study at Clemson University

In Chemical Engineering



Coming Up for Air

No matter where you do your graduate work, your nose will be in your books and your mind on your research. But at Clemson University, there's something for you when you *can* stretch out for a break.

Like breathing good air. Or swimming, fishing, sailing and water skiing in the clean lakes. Or hiking in the nearby Blue Ridge Mountains. Or driving to South Carolina's famous beaches for a weekend. Something that can *really* relax you.

All this and a top-notch Chemical Engineering Department, too.

With active research and teaching in polymer processing, composite materials, process automation, computer simulation of fluids, thermodynamics, catalysis, membrane separation, pollution control, and pulp and paper operations — what more do you need?

The University

Clemson, the land-grant university of South Carolina, offers 62 undergraduate and 61 graduate fields of study in its nine academic colleges. Present on-campus enrollment is about 12,000 students, one-third of whom are in the College of Engineering. There are about 2,600 graduate students. The 1,400-acre campus is located on the shores of Lake Hartwell in South Carolina's Piedmont, and is midway between Charlotte, N.C., and Atlanta, Ga.

The Faculty

Forest C. Alley

William B. Barlage, Jr.

Charles H. Barron, Jr.

John N. Beard, Jr.

William F. Beckwith

Dan D. Edie

Charles H. Gooding

James M. Haile

Stephen S. Melsheimer

Joseph C. Mullins

Amod A. Ogale

Richard W. Rice

Mark C. Thies

Programs lead to the M.S. and Ph.D. degrees.

Financial aid, including fellowships and assistantships, is available.

For Further Information

For further information and a descriptive brochure, write:

Graduate Coordinator

Department of Chemical Engineering

Earle Hall

Clemson University

Clemson, South Carolina 29634



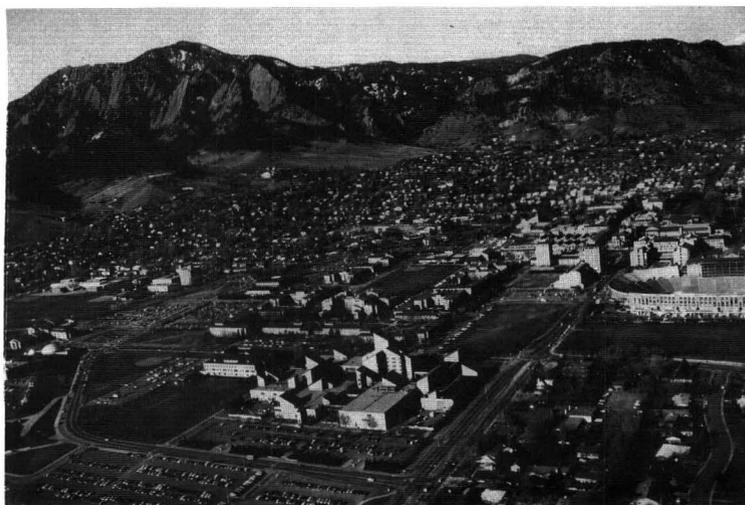
CLEMSON
UNIVERSITY

College of Engineering

UNIVERSITY OF COLORADO, BOULDER

GRADUATE STUDY
IN CHEMICAL ENGINEERING

M.S. and Ph.D. Programs



● FACULTY AND RESEARCH INTERESTS ●

DAVID E. CLOUGH, Associate Professor,
Associate Dean for Academic Affairs
Ph.D. (1975), University of Colorado
Fluidization, Process Control

ROBERT H. DAVIS, Assistant Professor
Ph.D. (1983), Stanford University
Fluid Dynamics of Suspensions, Biotechnology

JOHN L. FALCONER, Professor
Ph.D. (1974), Stanford University
Heterogeneous Catalysis, Surface Science

R. IGOR GAMOW, Associate Professor
Ph.D. (1967), University of Colorado
Biophysics, Bioengineering

PAUL G. GLUGLA, Assistant Professor
Ph.D. (1977), University of Illinois
*Ionic Solutions, Thermodynamics,
Membrane Separations*

DHINAKAR S. KOMPALA, Assistant Professor
Ph.D. (1984), Purdue University
*Biochemical Engineering, Bioseparations,
Bioreactor Design*

WILLIAM B. KRANTZ, Professor
Ph.D. (1968), University of California, Berkeley
*Membranes, Geophysical Fluid Mechanics, Coal
Gasification, Transport Processes in Permafrost*

LEE L. LAUDERBACK, Assistant Professor
Ph.D. (1982), Purdue University
*Surface Science, Heterogeneous Catalysis,
Molecular Dynamics*

W. FRED RAMIREZ, Professor
Ph.D. (1965), Tulane University
*Optimal Control and Identification of Chemical,
Biochemical, and Energy Recovery Processes*

ROBERT L. SANI, Professor
Ph.D. (1963), University of Minnesota
*Numerical Techniques in Fluid Dynamics,
Membranes*

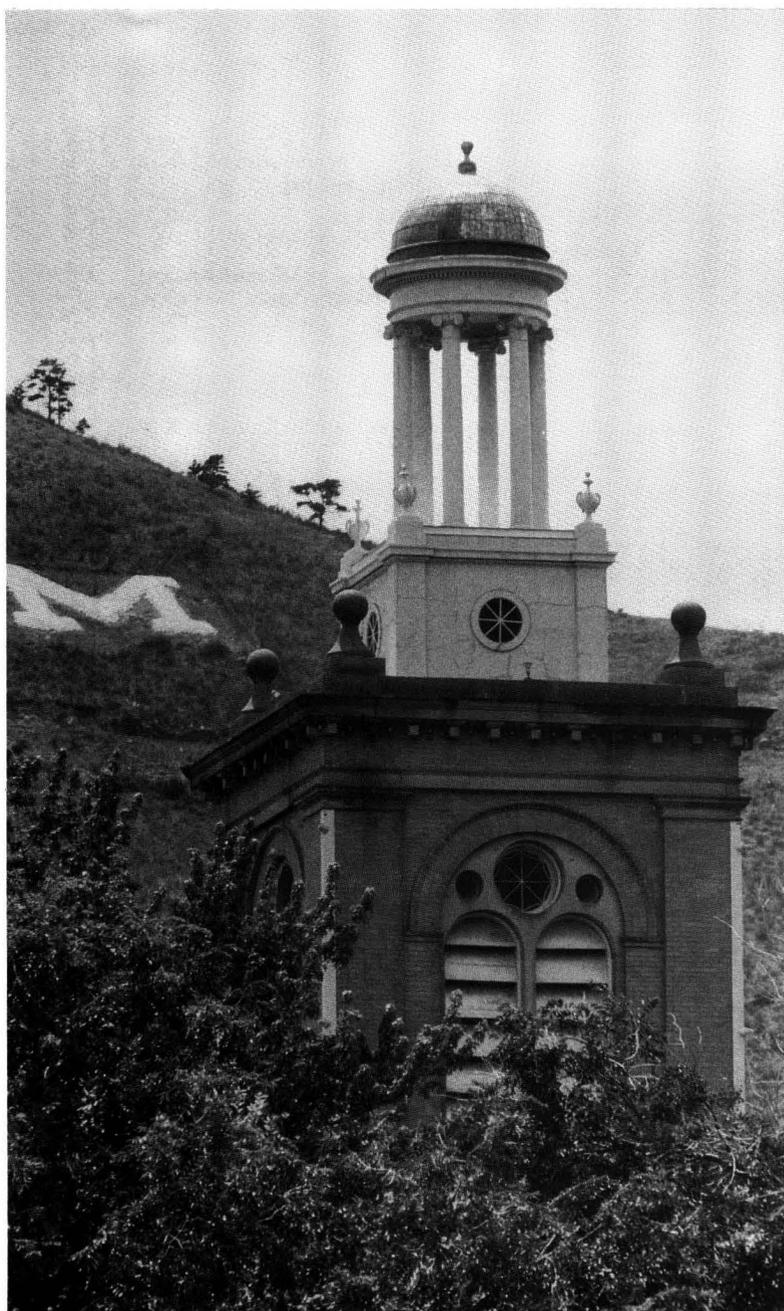
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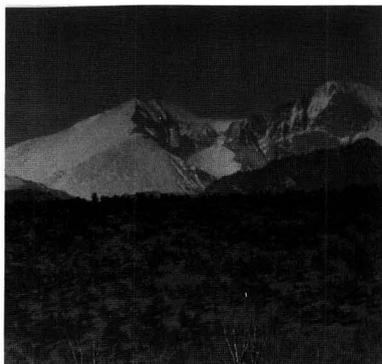
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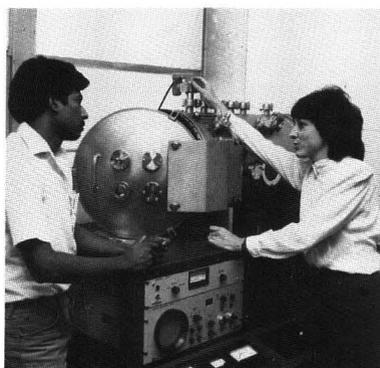
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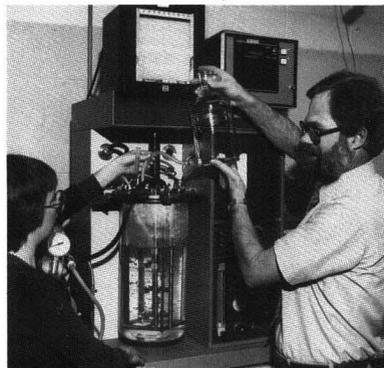


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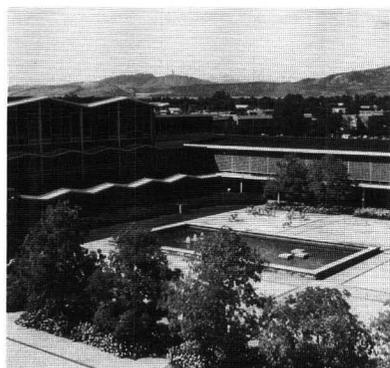
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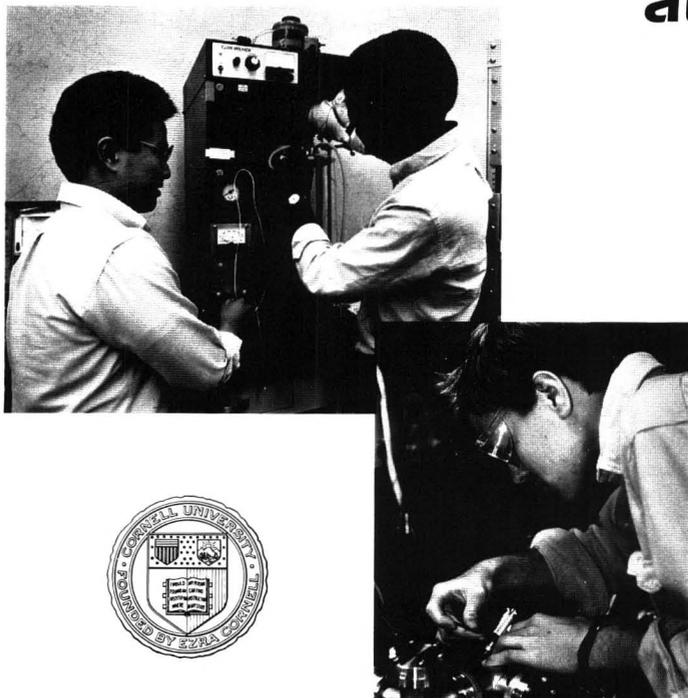
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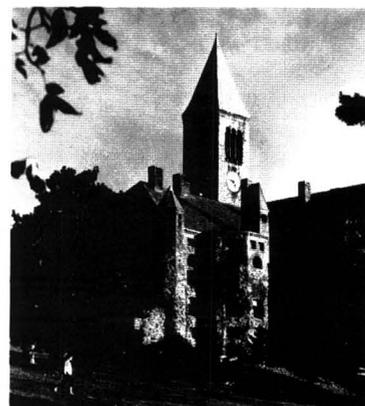
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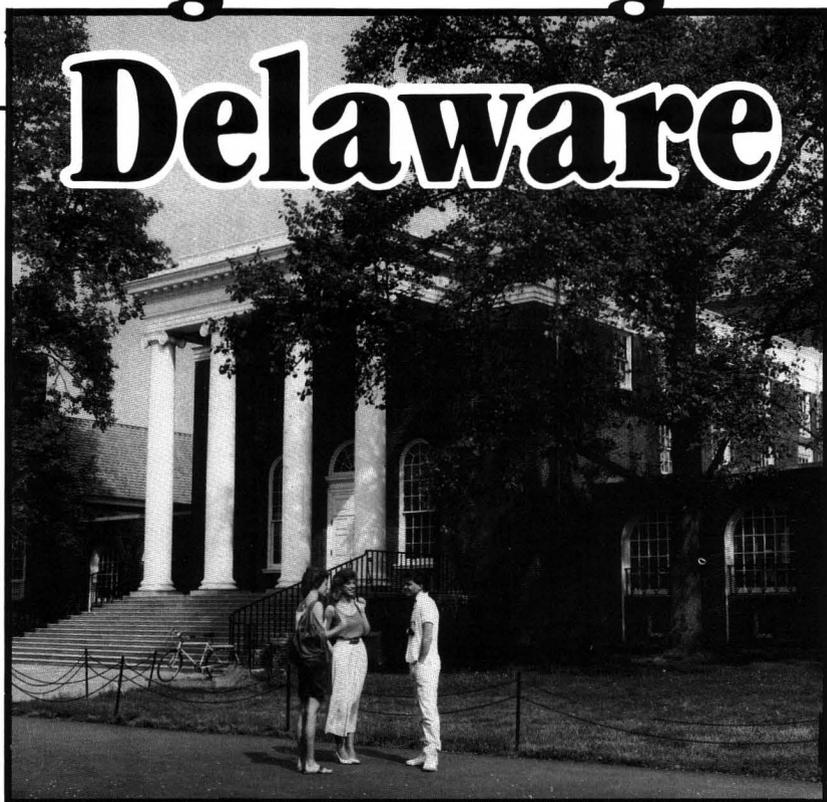
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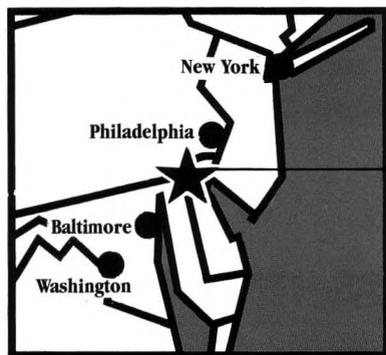
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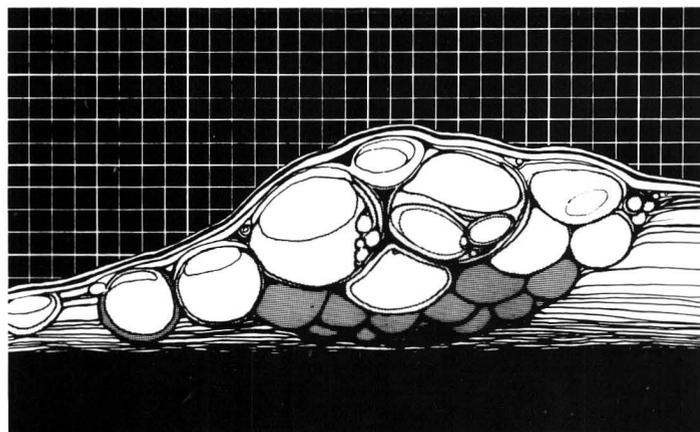
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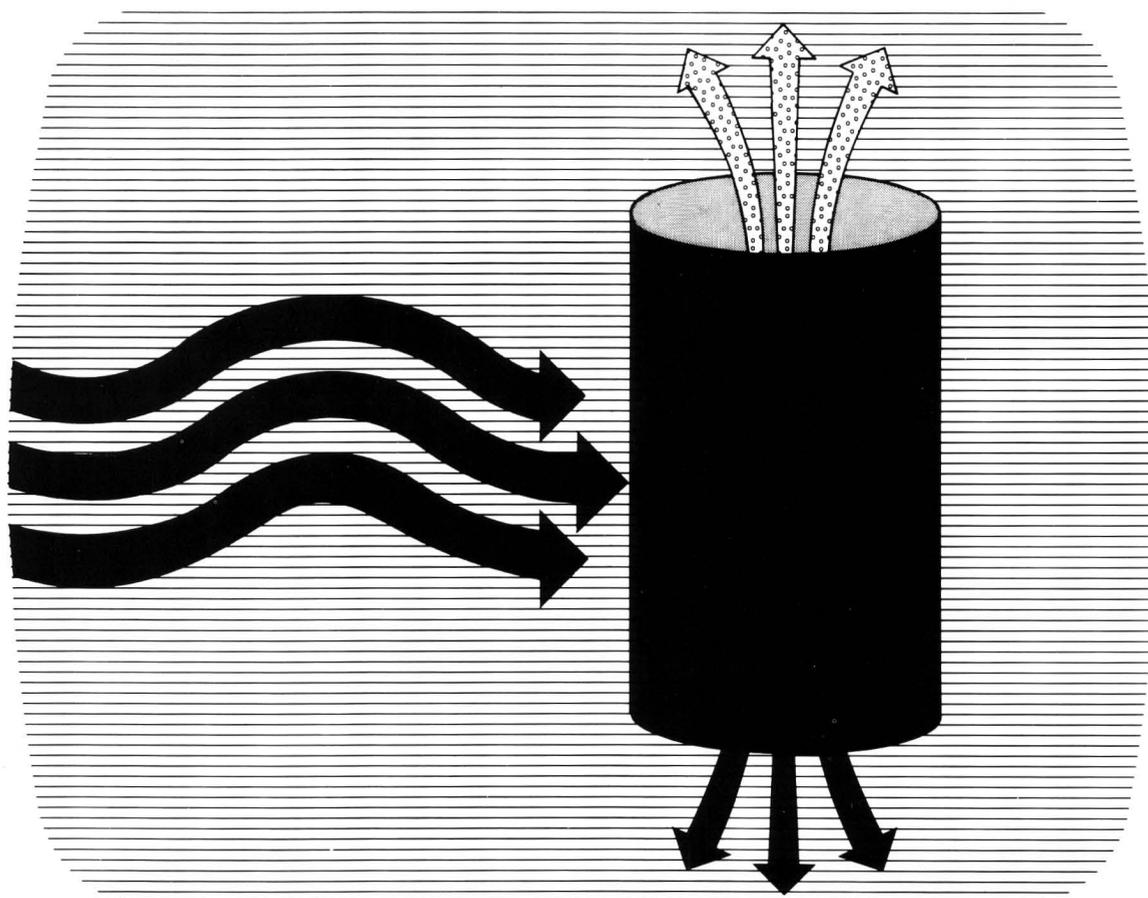
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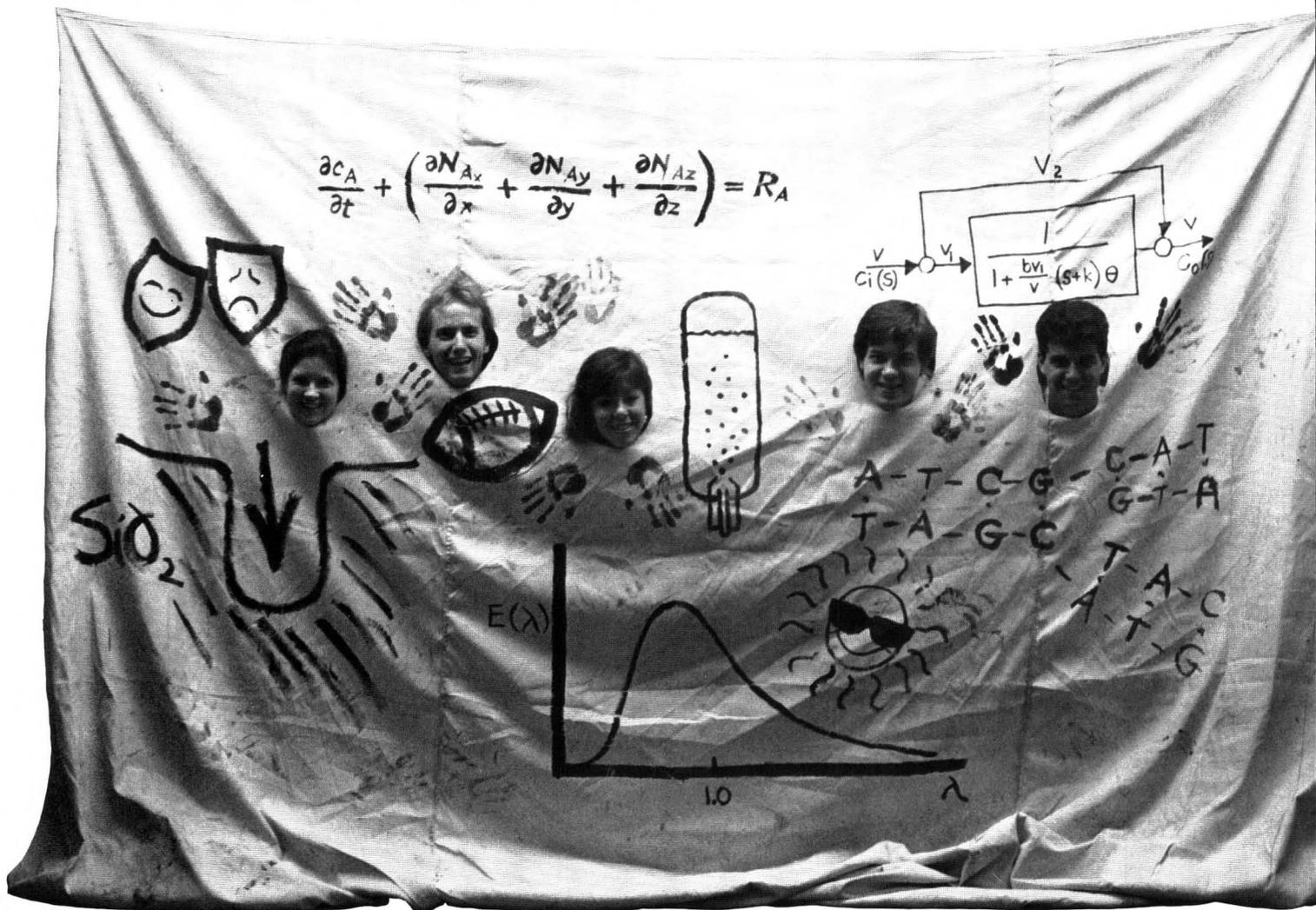
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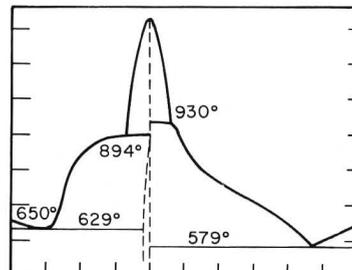
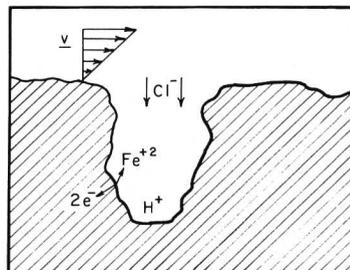
Joachim Floess Ph.D., Massachusetts Inst. of Tech., 1985 Assistant Professor	Reaction engineering with primary focus on the pyrolysis of oil shale and coal, energy technology environmental controls
Richard D. Gonzalez Ph.D., The Johns Hopkins University, 1965 Professor	Heterogeneous catalysis and surface chemistry, catalysis by supported metals, subseabed radioactive waste disposal studies, clay chemistry
John H. Kiefer Ph.D., Cornell University, 1961 Professor	Kinetics of gas reactions, energy transfer processes, laser diagnostics
G. Ali Mansoori Ph.D., University of Oklahoma, 1969 Professor	Thermodynamics and statistical mechanics of fluids, solids and solutions, kinetics of liquid reactions, solar energy
Irving F. Miller Ph.D., University of Michigan, 1960 Professor and Head	Lipid microencapsulation, adsorption and surface reactions, membrane transport, synthetic blood, biorheology
Sohail Murad Ph.D., Cornell University, 1979 Associate Professor	Thermodynamics and transport properties of fluids, computer simulation and statistical mechanics of liquids and liquid mixtures
John Regalbuto Ph.D., University of Notre Dame, 1986 Assistant Professor	Heterogeneous catalysis: promoted and bifunctional catalysis, characterization of solids and solid surfaces, heterogeneous reaction kinetics
Satish C. Saxena Ph.D., Calcutta University, 1956 Professor	Transport properties of fluidized solids, heat and mass transfer, isotope separation, fixed and fluidized bed combustion, indirect coal liquefaction
Stephen Szepe Ph.D., Illinois Institute of Technology, 1966 Associate Professor	Catalysis, chemical reaction engineering, energy transmission, modelling and optimization
Raffi M. Turian Ph.D., University of Wisconsin, 1964 Professor, Director of Graduate Studies	Slurry transport, suspension and complex fluid flow and heat transfer, porous media processes, mathematical analysis and approximation
David Willcox Ph.D., Northwestern University, 1985 Assistant Professor	Structure sensitivity of oxide catalysts for selective oxidation reactions, catalyst preparation techniques, artificial intelligence applied to descriptive kinetics

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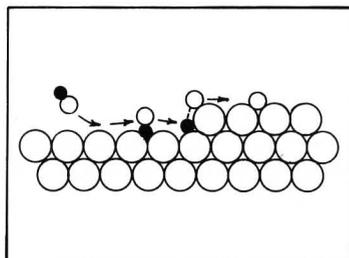
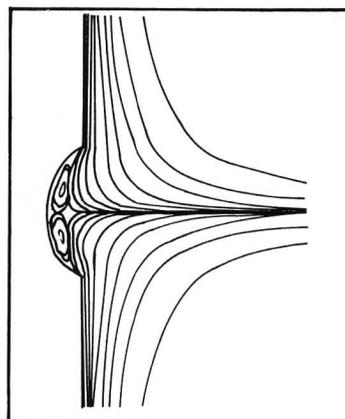
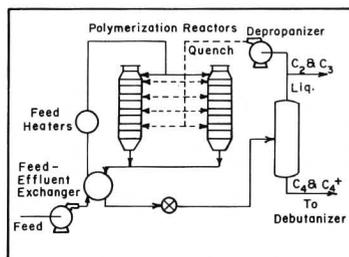
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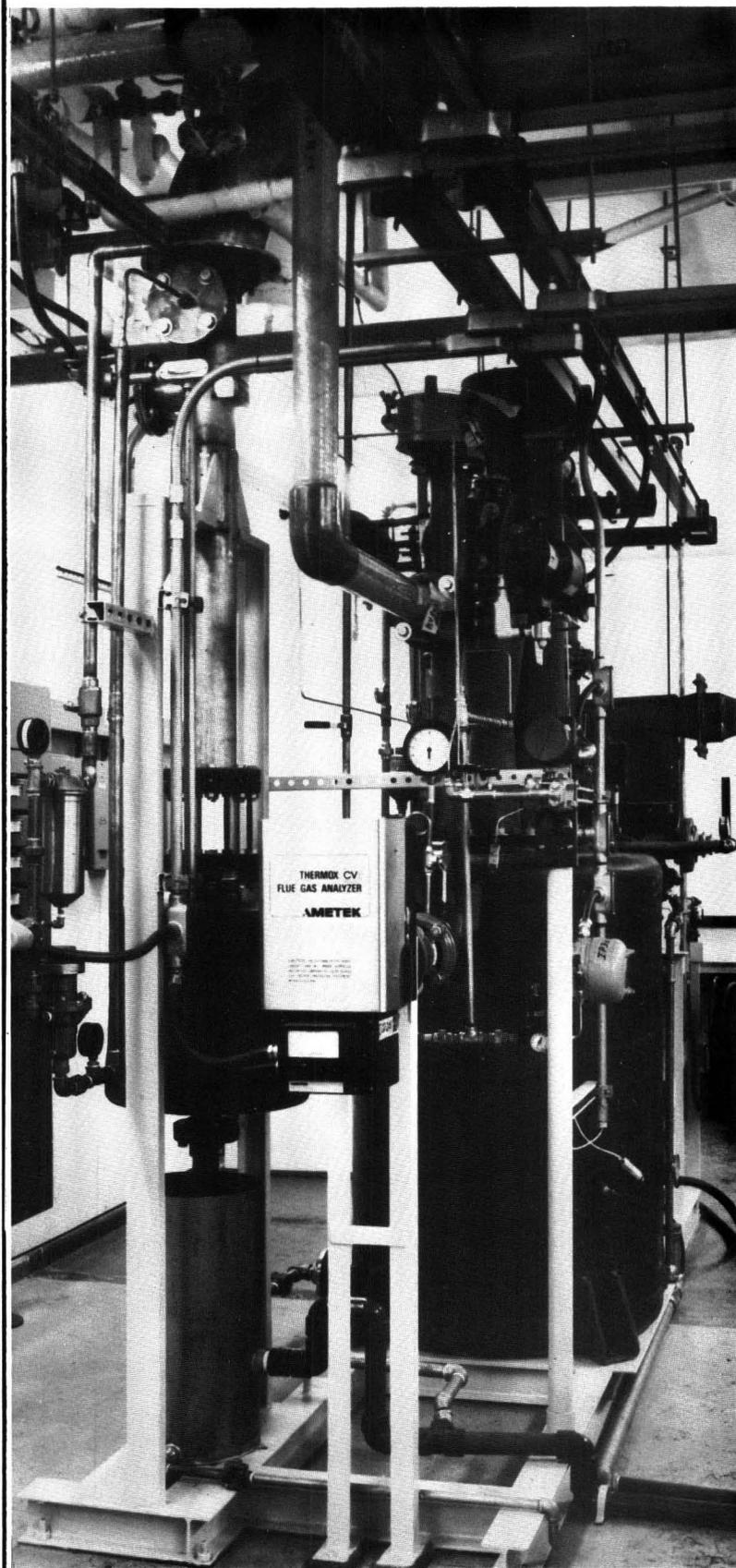
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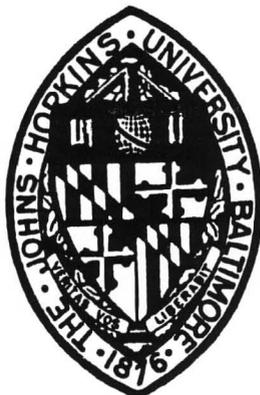
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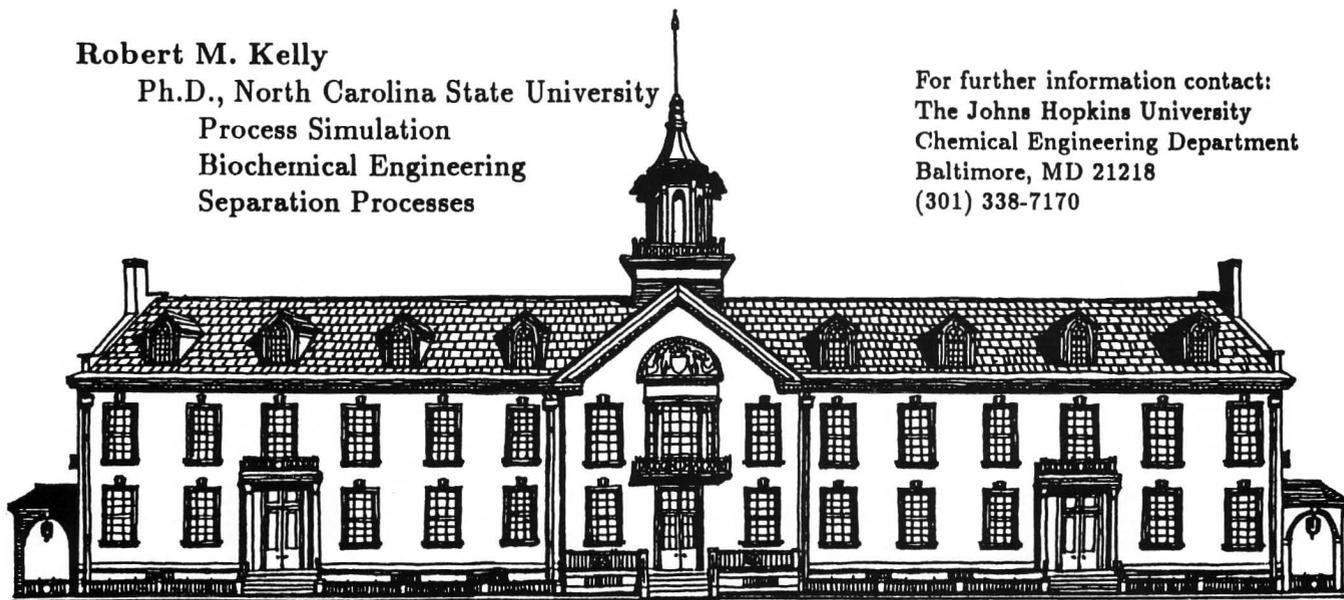
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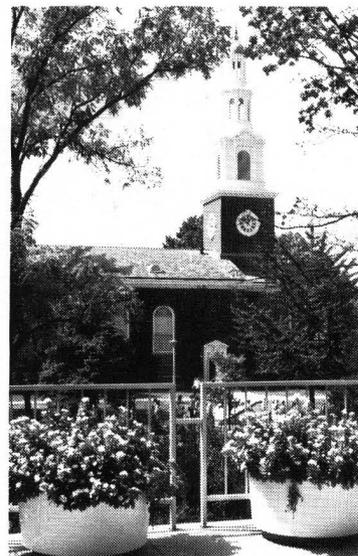
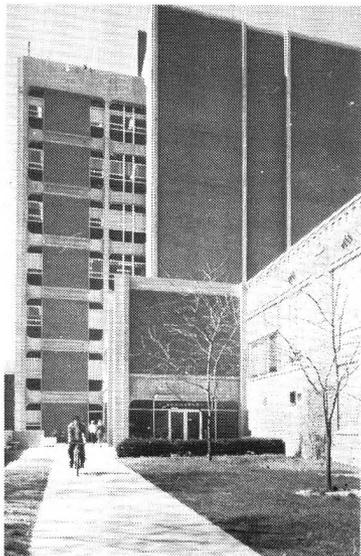
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DEPARTMENT OF CHEMICAL ENGINEERING M.S. and Ph.D. Programs

THE FACULTY AND THEIR RESEARCH INTERESTS

J. Berman, Ph.D., Northwestern
Biomedical Engineering; Cardiovascular
Transport Phenomena; Blood Oxygenation

D. Bhattacharyya, Ph.D.
Illinois Institute of Technology
Novel Separation Processes; Membranes;
Water Pollution Control

G. F. Crewe, Ph.D., West Virginia
Computer-Aided Process Design; Coal Liquefaction

C. E. Hamrin, Jr., Ph.D., Northwestern
Coal Liquefaction; Catalysis; Three-phase Reactors

G. P. Huffman, Ph.D., West Virginia
Coal Science; Mossbauer and EXAFS Spectroscopy

R. I. Kermode, Ph.D., Northwestern
Process Control and Economics

E. D. Moorhead, Ph.D., Ohio State
Dynamics of Electrochemical Processes; Computer
Measurement Techniques and Modeling

L. K. Peters, Ph.D., Pittsburgh
Atmospheric Transport; Aerosol Phenomena

A. K. Ray, Ph.D., Clarkson
Heat and Mass Transfer in Knudsen
Regime; Transport Phenomena

J. T. Schrodt, Ph.D., Louisville
Simultaneous Heat and Mass Transfer;
Fuel Gas Desulfurization

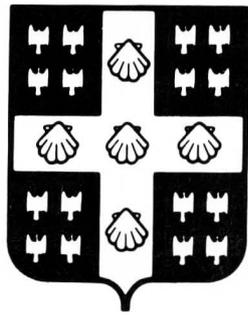
T. T. Tsang, Ph.D., Texas-Austin
Aerosol Dynamics in Uniform and Non-Uniform Systems

K. A. Ward, Ph.D., Carnegie-Mellon
Biomedical Engineering; Environmental Pharmacology;
Tumor Microcirculation; Synthetic and Biological
Membrane Transport

Fellowships and Research Assistantships are Available to Qualified Applicants
In Addition, Outstanding Students May Qualify for a McAdams Fellowship

For details write to:

R. I. Kermode, Director for Graduate Studies
Chemical Engineering Department
University of Kentucky
Lexington, Kentucky 40506-0046



UNIVERSITÉ LAVAL

Québec, Canada

Ph.D. and M.Sc. in Chemical Engineering

Research Areas

- *CATALYSIS (S. Kaliaguine)*
- *BIOCHEMICAL ENGINEERING (L. Choplin, A. LeDuy, R. W. J. Lencki, J.-R. Moreau, J. Thibault)*
- *ENVIRONMENTAL ENGINEERING (R.S. Ramalho, C. Roy)*
- *COMPUTER AIDED ENGINEERING (P.A. Tanguy)*
- *TECHNOLOGY MANAGEMENT (P.-H. Roy)*
- *MODELLING AND CONTROL (L. Cloutier, J.-C. Méthot, J. Thibault)*
- *RHEOLOGY AND POLYMER ENGINEERING (A. Ait-Kadi, L. Choplin, P.A. Tanguy)*
- *THERMODYNAMICS (R.S. Ramalho, S. Kaliaguine)*
- *CHEMICAL AND BIOCHEMICAL UPGRADING OF BIOMASS (S. Kaliaguine, A. LeDuy, C. Roy)*

Université Laval is a French speaking University. It provides the graduate student with the opportunity of learning French and becoming acquainted with French culture. Please write to:

Le Responsable du Comité d'Admission et de
Supervision

Département de génie chimique
Faculté des sciences et de génie
Université Laval
Sainte-Foy, Québec, Canada G1K 7P4

The Faculty

ABDELLATIF AIT-KADI
Ph.D. École Poly. Montréal
Professeur adjoint

LIONEL CHOPLIN
Ph.D. École Poly. Montréal
Professeur agrégé

LÉONCE CLOUTIER
D.Sc. Laval
Professeur titulaire

SERGE KALIAGUINE
D. Ing. I.G.C. Toulouse
Professeur titulaire

ANH LEDUY
Ph.D. Western Ontario
Professeur titulaire

ROBERT W.J. LENCKI
Ph.D. McGill
Professeur assistant

J.-CLAUDE MÉTHOT
D.Sc. Laval
Professeur titulaire

JEAN-R. MOREAU
Ph.D. M.I.T.
Professeur titulaire

RUBENS S. RAMALHO
Ph.D. Vanderbilt
Professeur titulaire

CHRISTIAN ROY
Ph.D. Sherbrooke
Professeur agrégé

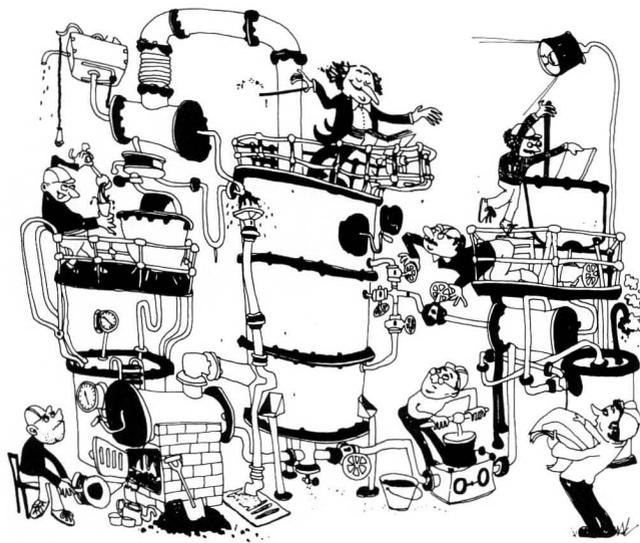
PAUL-H. ROY
Ph.D. Illinois Institute
of Technology
Professeur titulaire

PHILIPPE A. TANGUY
Ph.D. Laval
Professeur adjoint

JULES THIBAUT
Ph.D. McMaster
Professeur agrégé

Louisiana State University

CHEMICAL ENGINEERING GRADUATE SCHOOL



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Baton Rouge is the state capitol and home of the major state institution for higher education – LSU. Situated in the Acadian region, Baton Rouge blends the Old South and Cajun Cultures. The Port of Baton Rouge is a main chemical shipping point, and the city's economy rests heavily on the chemical and agricultural industries. The great outdoors provide excellent recreational activities year round, additionally the proximity of New Orleans provides for superb nightlife, especially during Mardi Gras.

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Bench Scale Fermentation Facilities

TO APPLY, CONTACT:

DIRECTOR OF GRADUATE INSTRUCTION

Department of Chemical Engineering

Louisiana State University

Baton Rouge, LA 70803

FACULTY

A.B. CORRIPIO (Ph.D., LSU)

Control, Simulation, Computer Aided Design

K.M. DOOLEY (Ph.D., Delaware)

Heterogeneous Catalysis, Reaction Engineering

G.L. GRIFFIN (Ph.D., Princeton)

Heterogeneous Catalysis, Surfaces, Materials Processing

F.R. GROVES (Ph.D., Wisconsin)

Control, Modeling, Separation Processes

D.P. HARRISON (Ph.D., Texas)

Fluid-Solid Reactions, Hazardous Wastes

A.E. JOHNSON (Ph.D., Florida)

Distillation, Control, Modeling

M. HJORTSØ (Ph.D., Univ. of Houston)

Biotechnology, Applied Mathematics

F.C. KNOPF (Ph.D., Purdue)

Computer Aided Design, Supercritical Processing

E. McLAUGHLIN (D.Sc., Univ. of London)

Thermodynamics, High Pressures, Physical Properties

R.W. PIKE (Ph.D., Georgia Tech)

Fluid Dynamics, Reaction Engineering, Optimization

J.A. POLACK (Sc.D., MIT)

Sugar Technology, Separation Processes

G.L. PRICE (Ph.D., Rice Univ.)

Heterogeneous Catalysis, Surfaces

D.D. REIBLE (Ph.D., Caltech)

Transport Phenomena, Environmental Engineering

R.G. RICE (Ph.D., Pennsylvania)

Mass Transfer, Separation Processes

A.M. STERLING (Ph.D., Univ. of Washington)

Biomedical Engineering, Transport Properties, Combustion

L.J. THIBODEAUX (Ph.D., LSU)

Chemodynamics, Hazardous Waste

D.M. WETZEL (Ph.D., Delaware)

Physical Properties, Hazardous Wastes

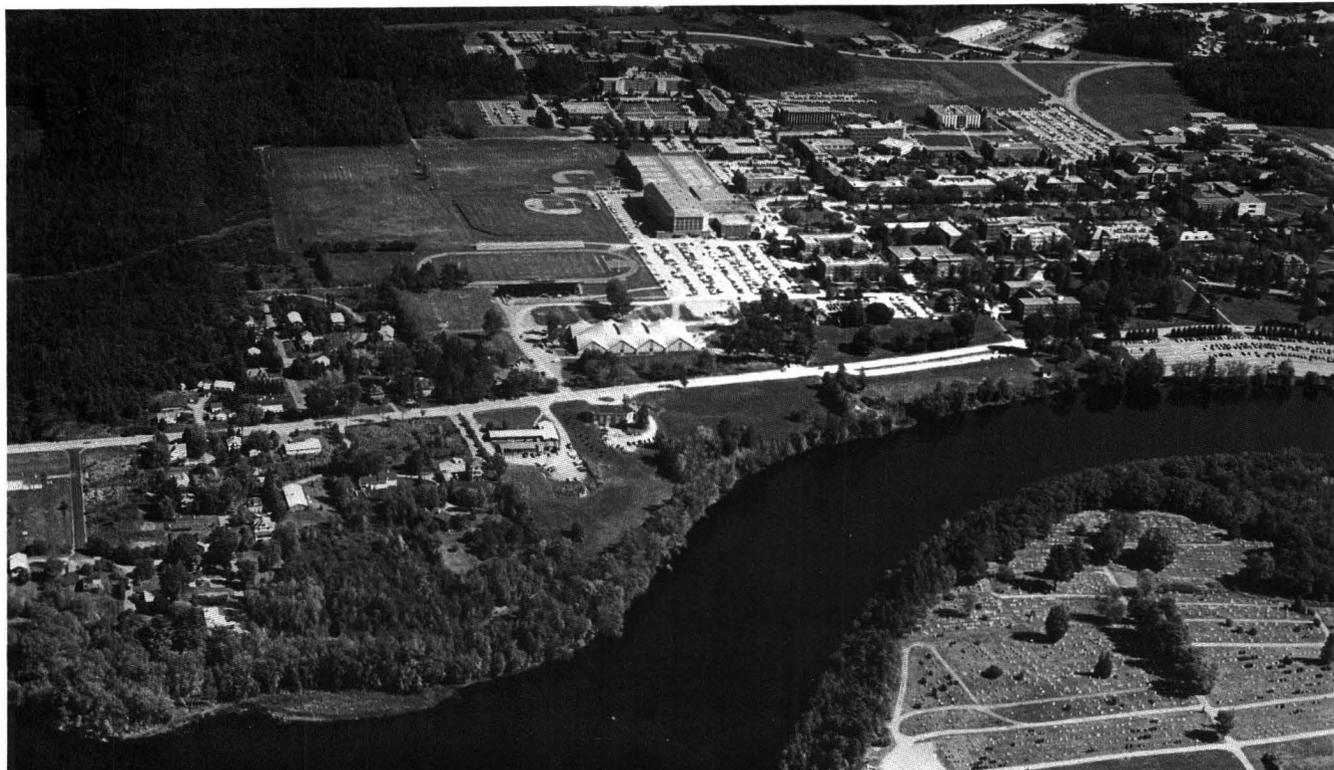
FINANCIAL AID

Fellowships and assistantships with tuition paid are available

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University of Maine



● Faculty and Research Interests ●

DOUGLAS BOUSFIELD

Ph.D. (U.C. Berkeley)
Fluid Mechanics, Rheology, Biochemical Engineering.

WILLIAM H. CECKLER

Sc.D. (M.I.T.)
Heat Transfer, Pressing & Drying Operations, Energy from Low BTU Fuels, Process Simulation & Modeling.

ALBERT CO

Ph.D. (Wisconsin)
Polymeric Fluid Dynamics, Rheology, Transport Phenomena, Numerical Methods.

JOSEPH M. GENCO

Ph.D. (Ohio State)
Process Engineering, Pulp and Paper Technology, Wood Delignification.

JOHN C. HASSLER

Ph.D. (Kansas State)
Process Control, Numerical Methods, Instrumentation and Real Time Computer Applications.

MARQUITA K. HILL

Ph.D. (U.C. Davis)
Separation Processes, Pulping Chemistry, Ultrafiltration.

JOHN J. HWALEK

Ph.D. (Illinois)
Liquid Metal Natural Convection, Electronics Cooling, Process Control Systems.

ERDOGAN KIRAN

Ph.D. (Princeton)
Polymer Physics & Chemistry, Supercritical Fluids, Thermal Analysis & Pyrolysis, Pulp & Paper Science.

DAVID J. KRASKE

Ph.D. (Inst. Paper Chemistry)
Pulp, Paper & Coating Technology, Additive Chemistry, Cellulose & Wood Chemistry.

JAMES D. LISIUS

Ph.D. (Illinois)
Electrochemical Engineering, Composite Materials, Coupled Mass Transfer.

KENNETH I. MUMMÉ

Ph.D. (Maine)
Process Simulation and Control, System Identification & Optimization.

HEMANT PENDSE

Ph.D. (Syracuse)
Colloidal Phenomena, Particulate & Multiphase Processes, Porous Media Modeling.

IVAR H. STOCKEL

Sc.D. (M.I.T.) (Chairman)
Droplet Formation, Fluidization, Pulp & Paper Technology.

EDWARD V. THOMPSON

Ph.D. (Polytechnic Institute of Brooklyn)
Thermal & Mechanical Properties of Polymers, Papermaking and Fiber Physics.

DOUGLAS L. WOERNER

Ph.D. (Washington)
Membrane Separations, Polymer Solutions, Colloid & Emulsion Technology.

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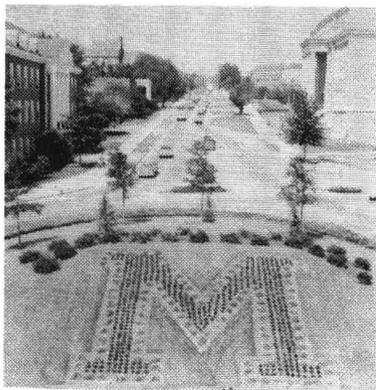
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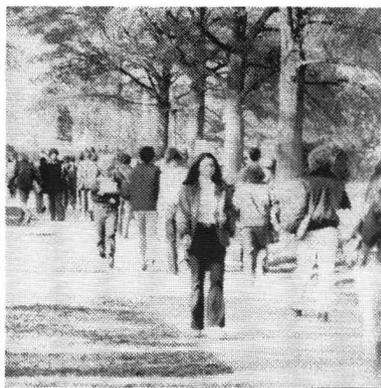
University of Maryland

College Park



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Faculty:

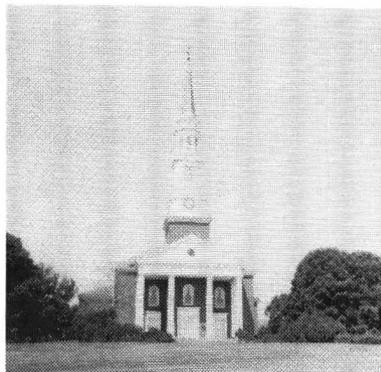
Odd A. Asbjornsen
Robert B. Beckmann
Richard V. Calabrese
Kyu Y. Choi
Larry L. Gasner
James W. Gentry
Keshava P. Halemane
Yih-Yun Hsu
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Thomas M. Regan
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Theodore G. Smith
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Separation Processes
Simulation
Systems Engineering
Turbulence and Mixing

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Chemical Engineering Graduate Studies
Department of Chemical and Nuclear Engineering
University of Maryland
College Park, Md. 20742



UNIVERSITY of MASSACHUSETTS

Amherst

The Chemical Engineering Department at the University of Massachusetts offers graduate programs leading to M.S. and Ph.D. degrees in Chemical Engineering. Active research areas include polymer engineering, catalysis, design, and basic engineering sciences. Close coordination characterizes research in polymers which can be conducted in either the Chemical Engineering Department or the Polymer Science and Engineering Department. Financial aid, in the form of research assistantships and teaching assistantships, is available. Course of study and area of research are selected in consultation with one or more of the faculty listed below.



For further details, please write to

Prof. M. F. Doherty
Graduate Program Director
Dept. of Chemical Engineering
University of Massachusetts
Amherst, Mass. 01003

or

Prof. D. A. Tirrell
Graduate Program Director
Dept. of Polymer Science and Engineering
University of Massachusetts
Amherst, Mass. 01003

**Joint appointments in Chemical Engineering and Polymer Science and Engineering*

• CHEMICAL ENGINEERING •

- M. A. BURNS** Biochemical engineering, Chromatographic separations
- W. C. CONNER** Catalysis, Kinetics, Surface diffusion
- M. F. DOHERTY** Distillation, Thermodynamics, Design
- J. M. DOUGLAS** Process design and control, Reactor engineering
- V. HAENSEL** Catalysis, Kinetics
- M. P. HAROLD** Kinetics and Reactor Engineering
- R. S. KIRK** Kinetics, Ebullient bed reactors
- R. L. LAURENCE*** Polymerization reactors, Fluid mechanics
- M. F. MALONE** Rheology, Polymer processing, Design
- P. A. MONSON** Statistical mechanics
- K. M. NG** Enhanced oil recovery, Two-phase flows
- J. M. OTTINO*** Mixing, Fluid mechanics, Polymer engineering
- M. VANPEE** Combustion, Spectroscopy
- P. R. WESTMORELAND** Combustion, Plasma processing
- H. H. WINTER*** Polymer rheology and processing, Heat transfer
- B. E. YDSTIE** Process control

• POLYMER SCIENCE AND ENGINEERING •

- J. C. W. CHIEN** Polymerization catalysts, Biopolymers, Polymer degradation
- R. J. FARRIS** Polymer composites, Mechanical properties, Elastomers
- D. A. HOAGLAND*** Hydrodynamic chromatography separations
- S. L. HSU** Polymer spectroscopy, Polymer structure analysis
- F. E. KARASZ** Polymer transitions, Polymer blends, Conducting polymers
- R. W. LENZ*** Polymer synthesis, Kinetics of polymerization
- W. J. MacKNIGHT** Viscoelastic and mechanical properties of polymers
- T. J. McCARTHY** Polymer synthesis, Polymer surfaces
- M. MUTHUKUMAR** Statistical mechanics of polymer solutions, gels, and melts
- R. S. PORTER** Polymer rheology, Polymer processing
- R. S. STEIN** Polymer crystallinity and morphology, Characterization
- D. A. TIRRELL** Polymer synthesis and membranes
- E. I. THOMAS*** Electron microscopy, Polymer morphology, x-Ray scattering

CHEMICAL ENGINEERING AT MIT

FACULTY

J. Wei, Department Head	J. P. Longwell
R. C. Armstrong	E. W. Merrill
R. F. Baddour	C. M. Mohr
J. M. Beér	R. C. Reid
E. D. Blankshtein	A. F. Sarofim
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R. A. Brown	H. H. Sawin
R. E. Cohen	K. A. Smith
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C. Cooney	G. N. Stephanopoulos
W. M. Deen	M. Stephanopoulos
L. B. Evans	U. W. Suter
K. K. Gleason	J. W. Tester
T. A. Hatton	P. S. Virk
J. B. Howard	D. I. C. Wang
M. Kramer	M. Yarmush

RESEARCH AREAS

Artificial Intelligence
Biomedical Engineering
Biotechnology
Catalysis and Reaction Engineering
Combustion
Computer-Aided Design
Electrochemistry
Energy Conversion
Environmental
Fluid Mechanics
Electronic Materials Processing
Kinetics and Reaction Engineering
Polymers
Process Dynamics and Control
Surfaces and Colloids
Transport Phenomena

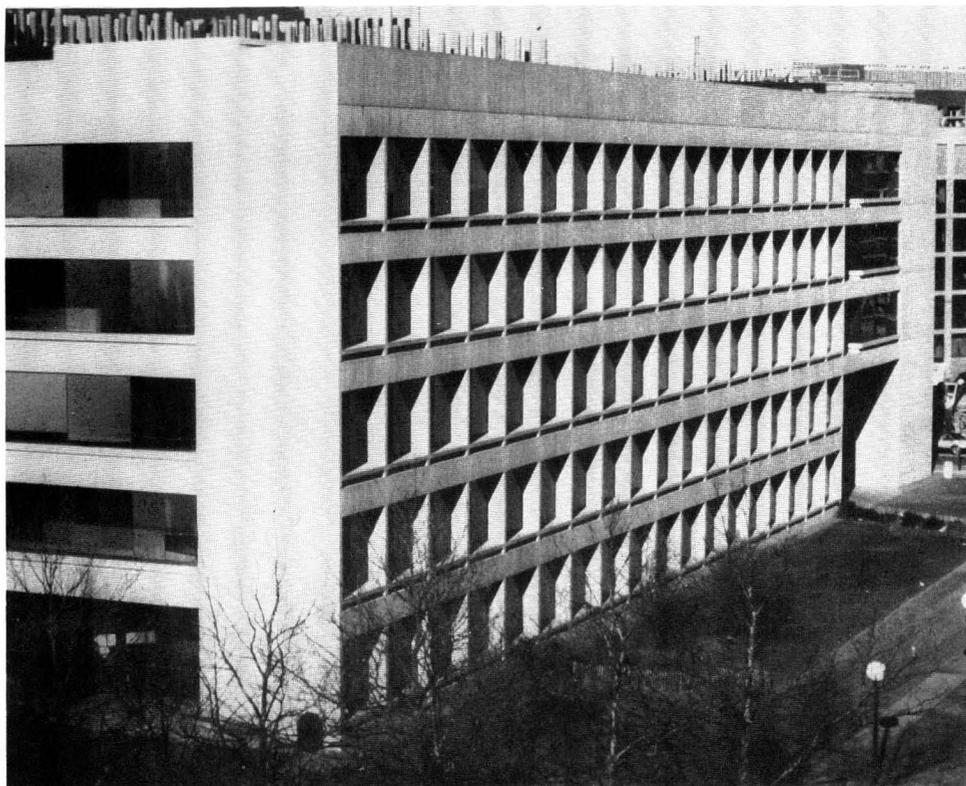


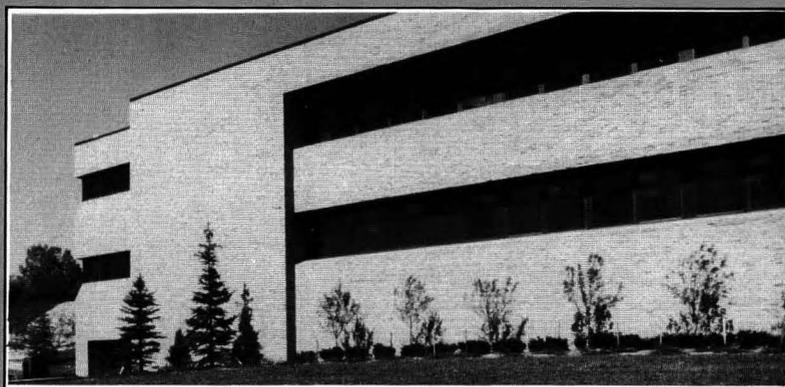
Photo by James Wei

MIT also operates the School of Chemical Engineering Practice, with field stations at the General Electric Company in Albany, New York, the Brookhaven National Lab at Long Island, New York, and the Dow Chemical Company in Midland, Michigan.

For Information

**Chemical Engineering Headquarters
Room 66-350
MIT
Cambridge, MA 02139**

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Professor Brice Carnahan • Graduate Program Advisor.

- Department of Chemical Engineering
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MICHIGAN STATE UNIVERSITY



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● FACULTY AND RESEARCH INTERESTS ●

D. K. ANDERSON, Chairman

Ph.D., 1960, University of Washington
Transport Phenomena, Diffusion in Polymer Solutions

K. A. BERGLUND

Ph.D., 1981, Iowa State University
Crystallization and Precipitation from Solution, Food Engineering, Applications of Raman Spectroscopy

D. M. BRIEDIS

Ph.D., 1981, Iowa State University
Biomedical Engineering, Thermodynamics of Living Systems, Biological Mineralization, Biochemical Engineering

R. E. BUXBAUM

Ph.D., 1981, Princeton University
Thermodynamics, Chemical Engineering of Nuclear Fusion, Theoretical and Experimental Diffusivities and Separation Rates, Bio-Physics

C. M. COOPER, Professor Emeritus

Sc.D., 1949, Massachusetts Institute of Technology
Thermodynamics and Phase Equilibria, Modeling of Transport Processes

L. T. DRZAL

Ph.D., 1974, Case Western Reserve University
Surface and Interfacial Phenomena, Adhesion, Composite Materials, Surface Characterization, Gas-Solid and Liquid-Solid Adsorption

H. E. GRETHLEIN

Ph.D., 1962, Princeton University
Biomass Conversion, Bio-Degradation, Waste Treatment, Bioprocess Development, Distillation, Biochemical Engineering

E. A. GRULKE

Ph.D., 1975, Ohio State University
Mass Transport Phenomena, Polymer Devolatilization, Biochemical Engineering, Food Engineering

M. C. HAWLEY

Ph.D., 1964, Michigan State University
Kinetics, Catalysis, Reactions in Plasmas, Polymerization Reactions, Composite Processing, Biomass Conversion, Reaction Engineering

K. JAYARAMAN

Ph.D., 1975, Princeton University
Polymer Rheology, Melt Blending of Polymers, Two-Phase Flow in Polymer Processing, Applied Acoustics

C. T. LIRA

Ph.D., 1985, University of Illinois at Urbana-Champaign
Thermodynamics and Phase Equilibria of Complex Systems, Supercritical Fluid Studies

D. J. MILLER

Ph.D., 1982, University of Florida
Kinetics and Catalysis, Reaction Engineering, Carbon Gasification, Thermal and Chemical Conversion of Biomass

C. A. PETTY

Ph.D., 1970, University of Florida
Fluid Mechanics, Turbulent Transport Phenomena, Solid-Fluid Separations

B. W. WILKINSON

Ph.D., 1958, Ohio State University
Energy Systems and Environmental Control, Nuclear Reactor, Radioisotope Applications

R. M. WORDEN

Ph.D., 1986, University of Tennessee
Biochemical Engineering, Immobilized Cell Technology, Bioreactor Dynamics and Control

FOR ADDITIONAL INFORMATION WRITE

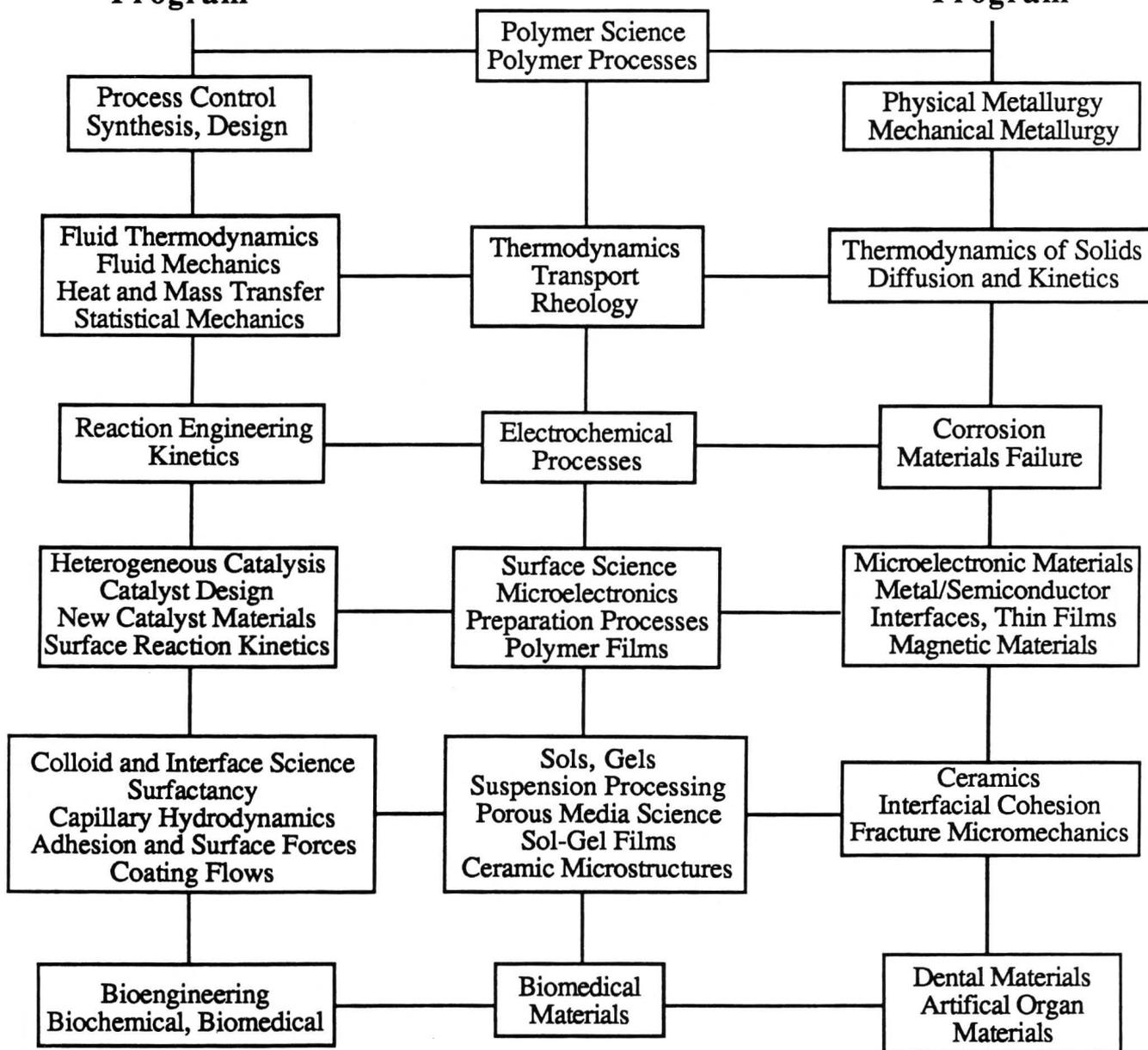
**Dr. Dennis J. Miller, Coordinator of Graduate Recruiting
Department of Chemical Engineering, 173 Engineering Building
Michigan State University
East Lansing, Michigan 48824-1226**

UNIVERSITY OF MINNESOTA

Chemical Engineering and Materials Science

Chemical Engineering Program

Materials Science Program



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R.W. Carr, Jr.	K.F. Jensen	D.A. Shores
E.L. Cussler	K.H. Keller	J.M. Sivertsen
J.S. Dahler	C.W. Macosko	W.H. Smyrl
H.T. Davis	J.L. Martins	F. Slienc
D.F. Evans	M.L. Mecartney	M. Tirrell
A. Franciosi	A.V. McCormick	R. Tranquillo
A.G. Fredrickson	R.A. Oriani	J.H. Weaver
C.J. Geankoplis	W.E. Ranz	H.S. White
W.W. Gerberich	L.D. Schmidt	

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Graduate Admissions
Chemical Engineering and
Materials Science
University of Minnesota
421 Washington Ave. S.E.
Minneapolis, MN 55455

Department of Chemical Engineering

UNIVERSITY OF MISSOURI — ROLLA

ROLLA, MISSOURI 65401

Contact Dr. J. W. Johnson, Chairman
Day Programs M.S. and Ph.D. Degrees

FACULTY AND RESEARCH INTERESTS

N. L. BOOK (Ph.D., Colorado)—Computer Aided Process Design, Bioconversion.

O. K. CROSSER (Ph.D., Rice)—Transport Properties, Kinetics, Catalysis.

M. E. FINDLEY (Ph.D., Florida)—Biochemical Studies, Biomass Utilization.

J. W. JOHNSON (Ph.D., Missouri)—Electrode Reactions, Corrosion.

A. I. LIAPIS (Ph.D., ETH-Zurich)—Adsorption, Freeze Drying, Modeling, Optimization, Reactor Design.

J. M. D. MAC ELROY (Ph.D., University College Dublin)—Transport Phenomena, Heterogeneous Catalysis, Drying, Statistical Mechanics.

D. B. MANLEY (Ph.D., Kansas)—Thermodynamics, Vapor-Liquid Equilibrium.

P. NEOGI (Ph.D., Carnegie-Mellon)—Interfacial Phenomena.

B. E. POLING (Ph.D., Illinois)—Kinetics, Energy Storage, Catalysis.

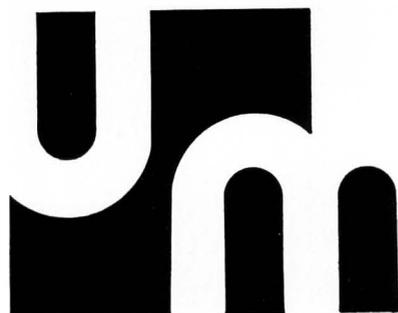
X B REED, JR. (Ph.D., Minnesota)—Fluid Mechanics, Drop Mechanics, Coalescence Phenomena, Liquid-Liquid Extraction, Turbulence Structure.

O. C. SITTON (Ph.D., Missouri-Rolla)—Bioengineering.

R. C. WAGGONER (Ph.D., Texas A&M)—Multistage Mass Transfer Operations, Distillation, Extraction, Process Control.

H. K. YASUDA (Ph.D., New York-Syracuse)—Polymer Membrane Technology, Thin-Film Technology, Plasma Polymerization, Biomedical Materials.

R. M. YBARRA (Ph.D., Purdue)—Rheology of Polymer Solutions, Chemical Reaction Kinetics.



Financial aid is obtainable in the form of Graduate and Research Assistantships, and Industrial Fellowships. Aid is also obtainable through the Materials Research Center.

Advanced Studies in Chemical Engineering at NJIT

NJIT, the public technological university of New Jersey, offering the Master of Science in Chemical Engineering, Master of Science, Degree of Engineer, and Doctor of Engineering Science.

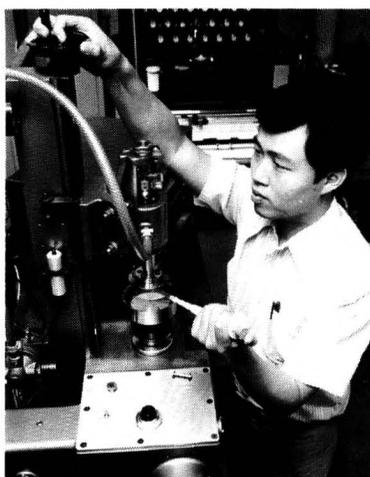
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Rey Chern (NCSU)	<i>Structure-property Relations; Membrane gas separations</i>
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Richard M. Felder (Princeton)	<i>Simulation and optimization; Chemical reaction engineering</i>
James K. Ferrell (NCSU)	<i>Coal gasification</i>
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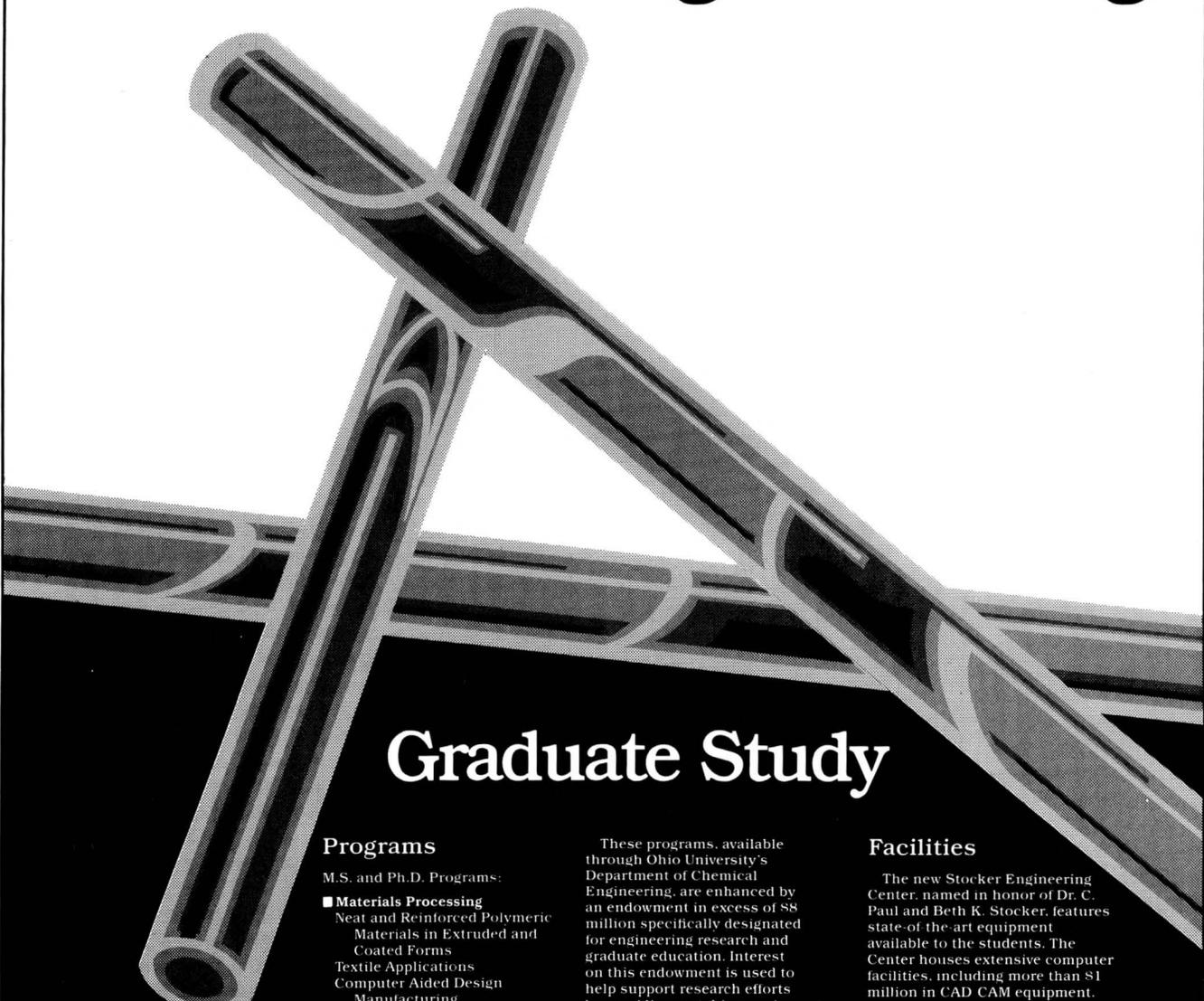
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- **Jeffrey J. Chalmers**, *Cornell 1988*, Biochemical Engineering, Protein Excretion and Production, and Immobilized Cell Reactor Design
- **James F. Davis**, *Northwestern 1982*, Artificial Intelligence, Computer Aided Design, and Process Control
- **L. S. Fan**, *West Virginia 1975*, Fluidization, Chemical & Biochemical Reaction Engineering, and Mathematical Modeling
- **Edwin R. Haering**, *Ohio State 1966*, Reaction Engineering, Catalysis, and Adsorption
- **Harry C. Hershey**, *Missouri-Rolla 1965*, Thermodynamics, and Drag Reduction
- **Kent S. Knaebel**, *Delaware 1980*, Mass Transfer, Separations, Computer-Aided Design, and Power Conversion Cycles
- **L. James Lee**, *Minnesota 1979*, Polymer Processing, Polymerization, and Rheology
- **Won-Kyoo Lee**, *Missouri-Columbia 1972*, Process Control, Computer Control, and Computer Aided Design
- **Umit Ozkan**, *Iowa State 1984*, Heterogeneous Catalysis, and Reaction Kinetics
- **Duane R. Skidmore**, *Fordham 1960*, Coal Processing, and Biochemical Engineering
- **Edwin E. Smith**, *Ohio State 1949*, Combustion, and Environmental Engineering
- **Thomas L. Sweeney**, *Case 1962*, Air Pollution Control, Heat Transfer, and Legal Aspects of Engineering
- **Shang-Tian Yang**, *Purdue 1984*, Biochemical Engineering and Biotechnology, Fermentation Processes, and Kinetics
- **Jacques L. Zakin**, *New York 1959*, Drag Reduction, Rheology, and Emulsions

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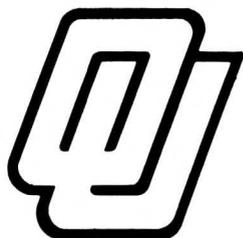
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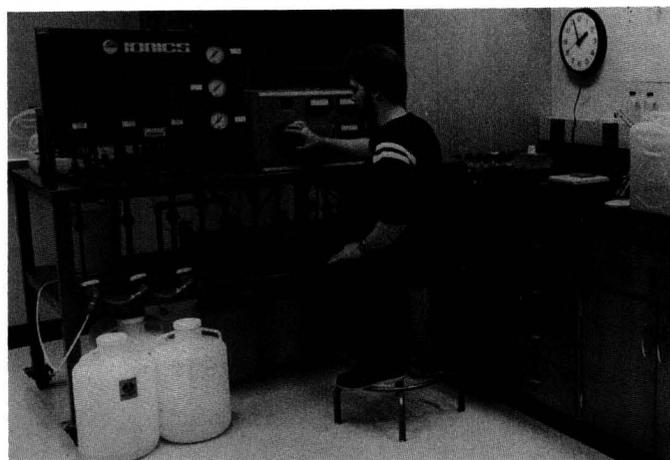
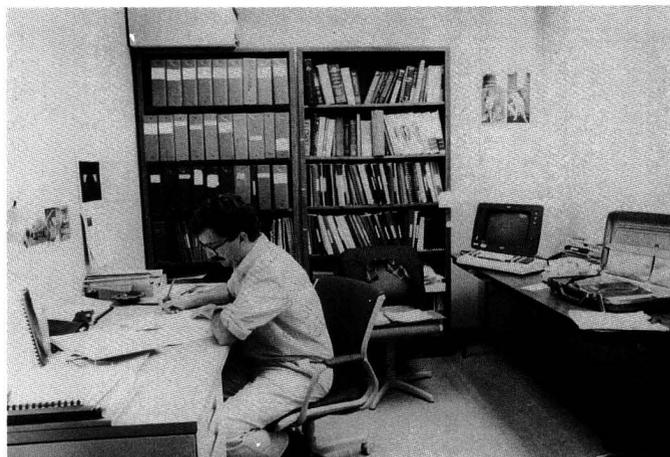
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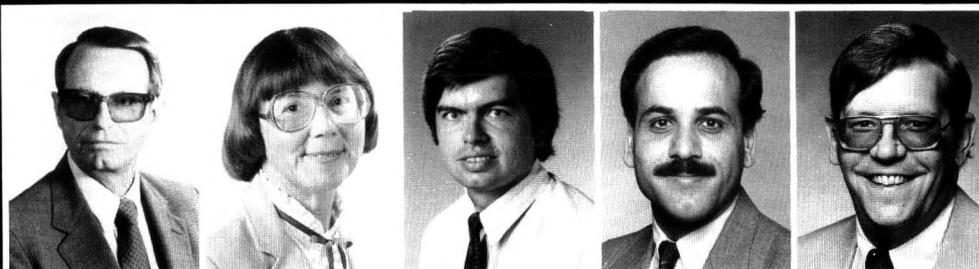
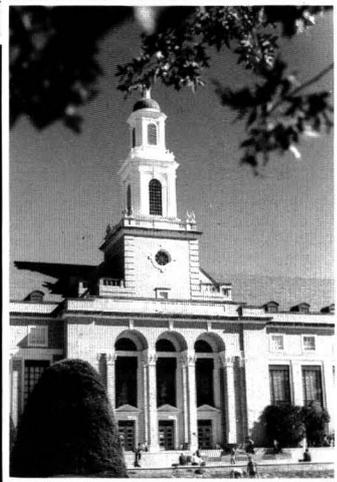
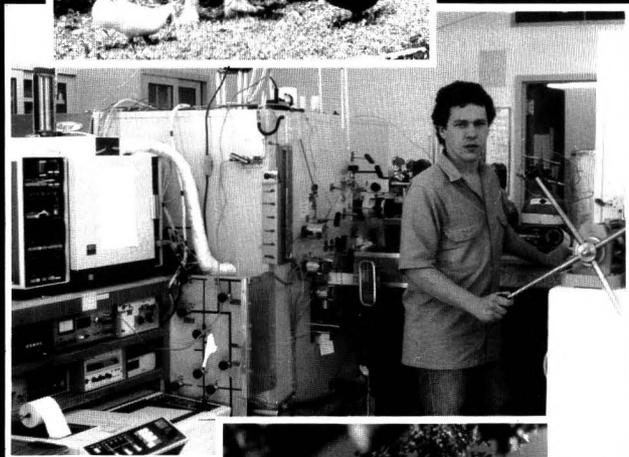
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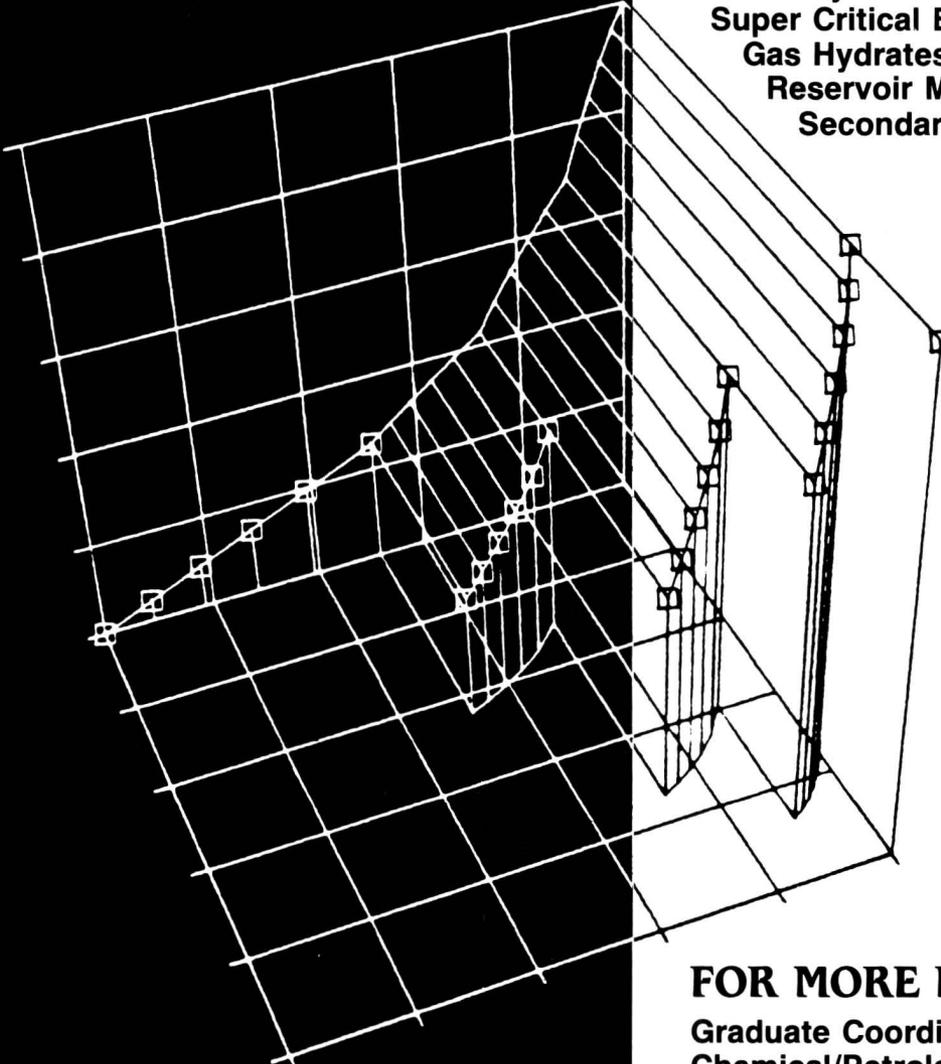
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Thermodynamics
Super Critical Extraction
Gas Hydrates
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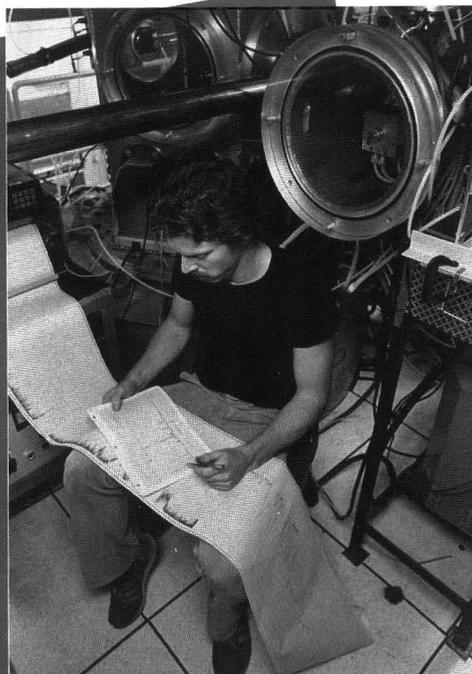


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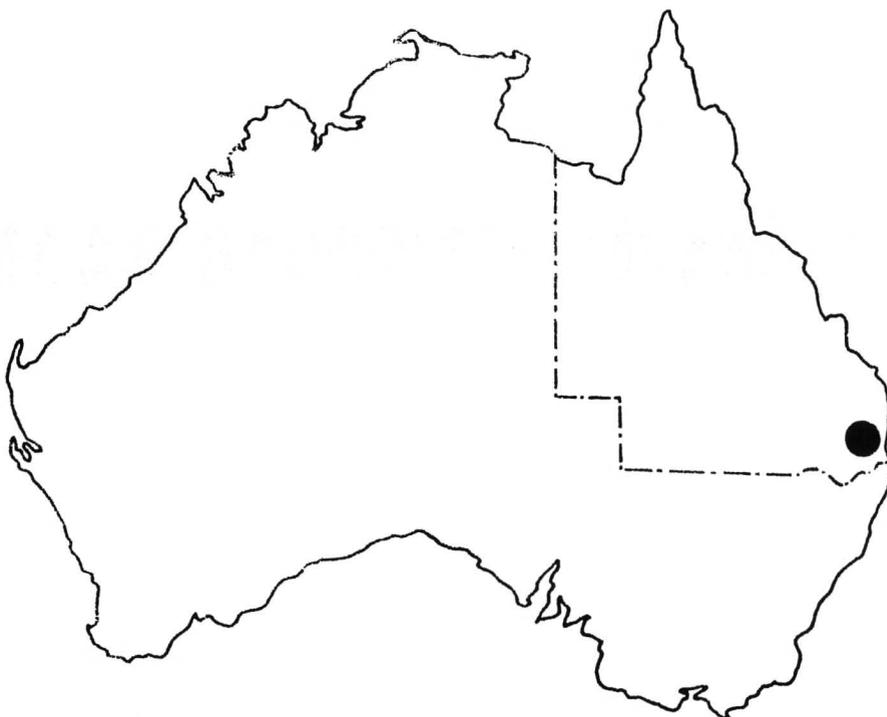
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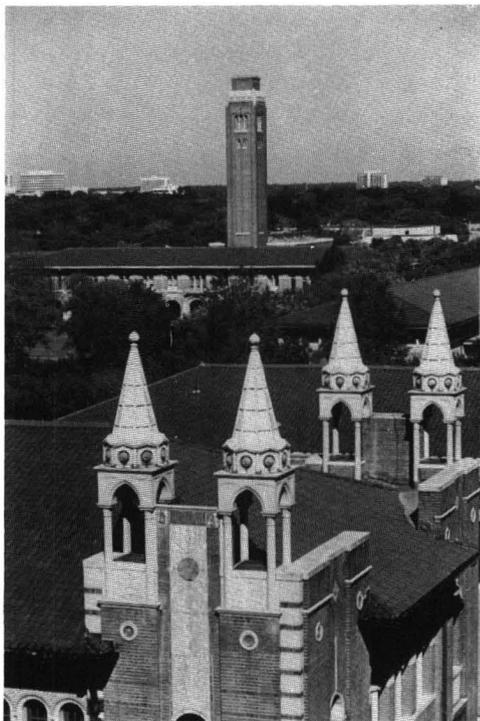
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- Separation engineering
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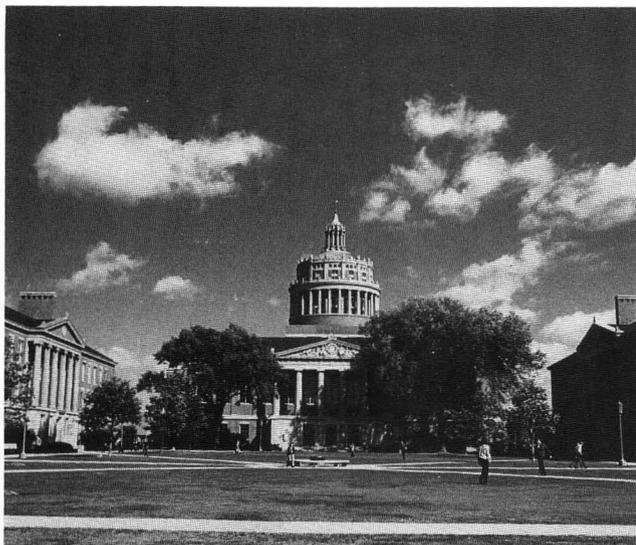
THE FACULTY

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Vice-president for administration.
- CONSTANTINE D. ARMENIADES (Case Western Reserve, 1969) Polymers and composites, biomaterials.
- SAM H. DAVIS, JR. (MIT, 1957) Dynamics of chemical systems, optimization, and process control.
- DEREK C. DYSON (London, 1966) Interfacial phenomena, hydrodynamic stability, and enhanced oil recovery.
- MICHAEL W. GLACKEN (M.I.T., 1987) Biochemical engineering, mammalian cell culture, immunological engineering
- J. DAVID HELLUMS (Michigan, 1961) Fluid mechanics and biomedical engineering
- JOE W. HIGHTOWER (Johns Hopkins, 1963) Kinetics and heterogeneous catalysis.
- RIKI KOBAYASHI (Michigan, 1951) Thermodynamics and transport properties, chromatography, coal liquefaction, and high-pressure properties.
- LARRY V. McINTIRE (Princeton, 1970) Rheology, fluid mechanics, and biomedical engineering.
- CLARENCE A. MILLER (Minnesota, 1969) Interfacial phenomena, enhanced oil recovery, detergency
- MARK A. ROBERT (Swiss Fed. Institute of Technology, 1980) Thermodynamics, statistical mechanics.
- KA-YIU SAN (CalTech, 1984) Biochemical engineering, and process control
- KYRIACOS ZYGOURAKIS (Minnesota, 1981) Chemical reaction engineering, computer applications for control and data acquisition.

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Transport Phenomena, Optical Materials*

E. H. CHIMOWITZ, Ph.D. 1982, Connecticut

*Computer-Aided Design, Super-Critical
Extraction, Control*

G. R. COKELET, Sc.D. 1963, M.I.T.

*Microcirculatory Transport Processes, Biomedical
Engineering*

M. R. FEINBERG, Ph.D. 1968, Princeton

Complex Reaction Systems, Applied Mathematics

J. R. FERRON, Ph.D. 1958, Wisconsin

*Molecular Transport Processes, Applied
Mathematics*

J. C. FRIEDLY, Ph.D. 1965, California (Berkeley)

Process Dynamics, Control, Heat Transfer

R. H. HEIST, Ph.D. 1972, Purdue

Nucleation, Solid State, Atmospheric Chemistry

J. JORNE, Ph.D. 1972, California (Berkeley)

*Electrochemical Engineering, Microelectronic
Processing, Theoretical Biology*

R. H. NOTTER, Ph.D. 1969, Washington (Seattle),
M.D. 1980, Rochester

*Biomedical Engineering, Lung Surfactants and
Pulmonary Disease, Aerosols*

H. J. PALMER, Ph.D. 1971, Washington (Seattle)

Interfacial Phenomena, Mass Transfer

H. SALTSBURG, Ph.D. 1955, Boston

*Surface Phenomena, Catalysis, Molecular
Scattering*

S. V. SOTIRCHOS, Ph.D. 1982, Houston

*Reaction Engineering, Combustion and
Gasification of Coal, Gas-Solid Reactions*

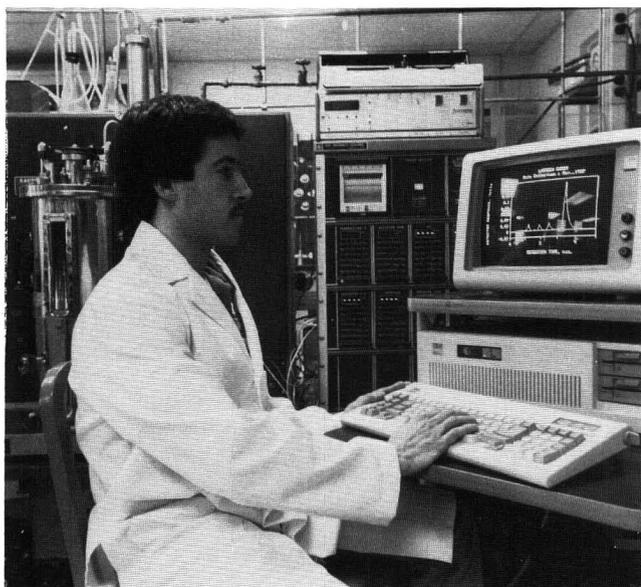
J. H. D. WU, Ph.D. 1987, M.I.T.

*Biochemical Engineering, Fermentation and
Industrial Microbiology*



RUTGERS

THE STATE UNIVERSITY OF NEW JERSEY



M.S. and Ph.D. PROGRAMS

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BIOCHEMICAL ENGINEERING FUNDAMENTALS

- MICROBIAL REACTIONS AND PRODUCTS • SOLUBLE AND IMMOBILIZED BIOCATALYSIS • BIOMATERIALS
- ENZYME AND FERMENTATION REACTORS • BIOTECHNOLOGY

ENGINEERING APPLICATIONS

- | | | |
|---|---|--|
| <ul style="list-style-type: none"> • BIOCHEMICAL TECHNOLOGY <ul style="list-style-type: none"> • INDUSTRIAL FERMENTATIONS • DOWNSTREAM PROCESSING • CONTROL OF FERMENTATION • FOOD PROCESSING • GENETIC ENGINEERING | <ul style="list-style-type: none"> • CHEMICAL TECHNOLOGY <ul style="list-style-type: none"> • EXPERT SYSTEMS/AI • ELECTROCHEMICAL ENGINEERING • POLYMER PROCESSING • SOLID STATE CATALYSIS • STATISTICAL THERMODYNAMICS | <ul style="list-style-type: none"> • MANAGEMENT OF HAZARDOUS WASTES <ul style="list-style-type: none"> • HAZARDOUS & TOXIC WASTE TREATMENT • QUALITY MANAGEMENT AND ANALYSIS • WASTEWATER RECOVERY AND REUSE • INCINERATION & RESOURCE RECOVERY • MICROBIAL DETOXIFICATION |
|---|---|--|

**FELLOWSHIPS AND
ASSISTANTSHIPS
ARE AVAILABLE**

For Application Forms and Further Information Write To:
Director of Graduate Program
 Dept. of Chemical and Biochemical Engineering
 Rutgers, The State University of New Jersey
 P.O. Box 909
 Piscataway, NJ 08855-0909



UNIVERSITY OF SOUTH CAROLINA

The Chemical Engineering Department offers M.S., M.E., and Ph.D. degrees. Graduate students have the opportunity to work closely with the faculty on research projects. Research and teaching stipends are available.

The University of South Carolina, with an enrollment of 23,800 on the Columbia campus, offers a variety of cultural and recreational activities. Columbia is part of one of the fastest growing areas in the country.

The Chemical Engineering Faculty

B.L. Baker, Distinguished Professor Emeritus, Ph.D., North Carolina State University, 1955 (*Process design, environment problems, ion transport*).

M.W. Davis, Jr., Weisiger Chair Professor, Ph.D., University of California (Berkeley), 1951 (*Kinetics and catalysis, chemical process analysis, solvent extraction, waste treatment*).

F.A. Gadala-Maria, Assistant Professor, Ph.D., Stanford University, 1979 (*Fluid mechanics, rheology*).

J.H. Gibbons, Professor, Ph.D., University of Pittsburgh, 1961 (*Heat transfer, fluid mechanics*).

E.L. Hanzevack, Jr., Associate Professor, Ph.D., Northwestern University, 1974 (*Two-phase flow, turbulence*).

F.P. Pike, Professor Emeritus, Ph.D., University of Minnesota, 1949 (*Mass transfer in liquid-liquid systems, vapor-liquid equilibria*).

T.G. Stanford, Assistant Professor, Ph.D., The University of Michigan, 1977 (*Chemical reactor engineering, mathematical modeling of chemical systems, process design, thermodynamics*).

V. Van Brunt, Associate Professor, Ph.D., University of Tennessee, 1974 (*Mass transfer, computer modeling, liquid extraction*).

J.W. Van Zee, Assistant Professor, Ph.D., Texas A & M University, 1984 (*Electrochemical systems, mathematical modeling, statistical applications*).

R.W. Wenig, Assistant Professor, Ph.D., Iowa State University, 1986 (*Catalysis, reaction kinetics, surface science*).

FOR FURTHER INFORMATION CONTACT

Prof. J.H. Gibbons
Chairman, Chemical Engineering
College of Engineering
University of South Carolina
Columbia, SC 29208



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H. Assadipour (PhD, Michigan Tech. U.)
J.A. Biesenberger (PhD, Princeton U.)
G.B. Delancey (PhD, Pittsburgh U.)
C.G. Gogos (PhD, Princeton U.)
D.M. Kalyon (PhD, McGill U.)
S. Kovenklioglu (PhD, Stevens)
D.H. Sebastian (PhD, Stevens)
H. Silla (PhD, Stevens)
K.K. Sirkar (PhD, Illinois U.)
C. Tsenoglou (PhD, Northwestern U.)

For application, contact:
Office of Graduate Studies
Stevens Institute of Technology
Hoboken, NJ 07030
201-420-5234

For additional information, contact:
Department of Chemistry and Chemical
Engineering
Stevens Institute of Technology
Hoboken, NJ 07030
201-420-5546

Financial aid is available to qualified students.

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FACULTY

Allen J. Barduhn (emeritus)

John C. Heydweiller

Cynthia S. Hirtzel

George C. Martin

Philip A. Rice (chairman)

Ashok S. Sangani

Klaus Schroder

James A. Schwarz

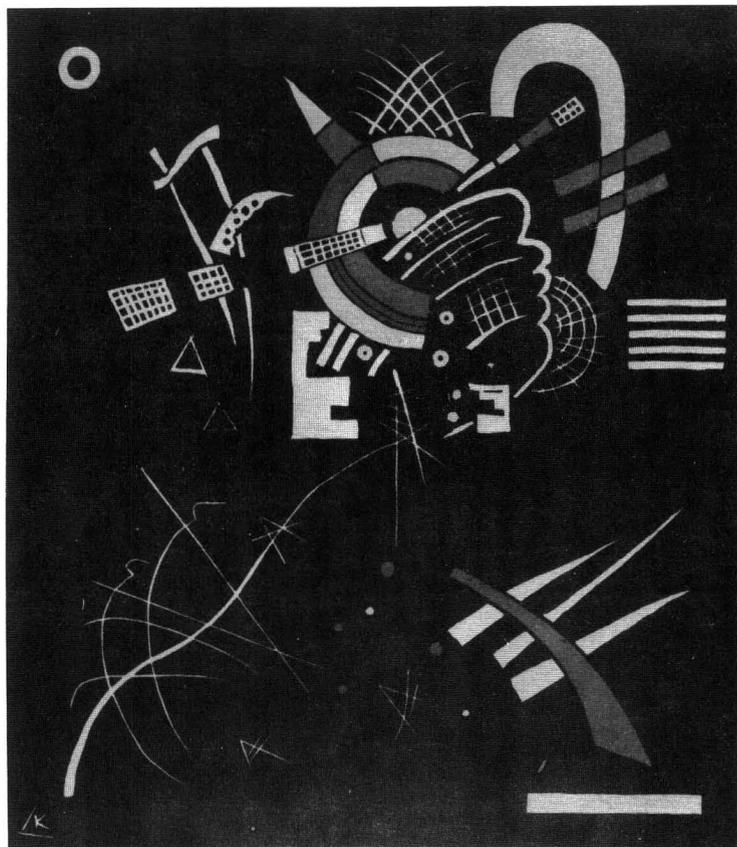
S. Alexander Stern

Lawrence L. Tavlarides

Chi Tien

for information:

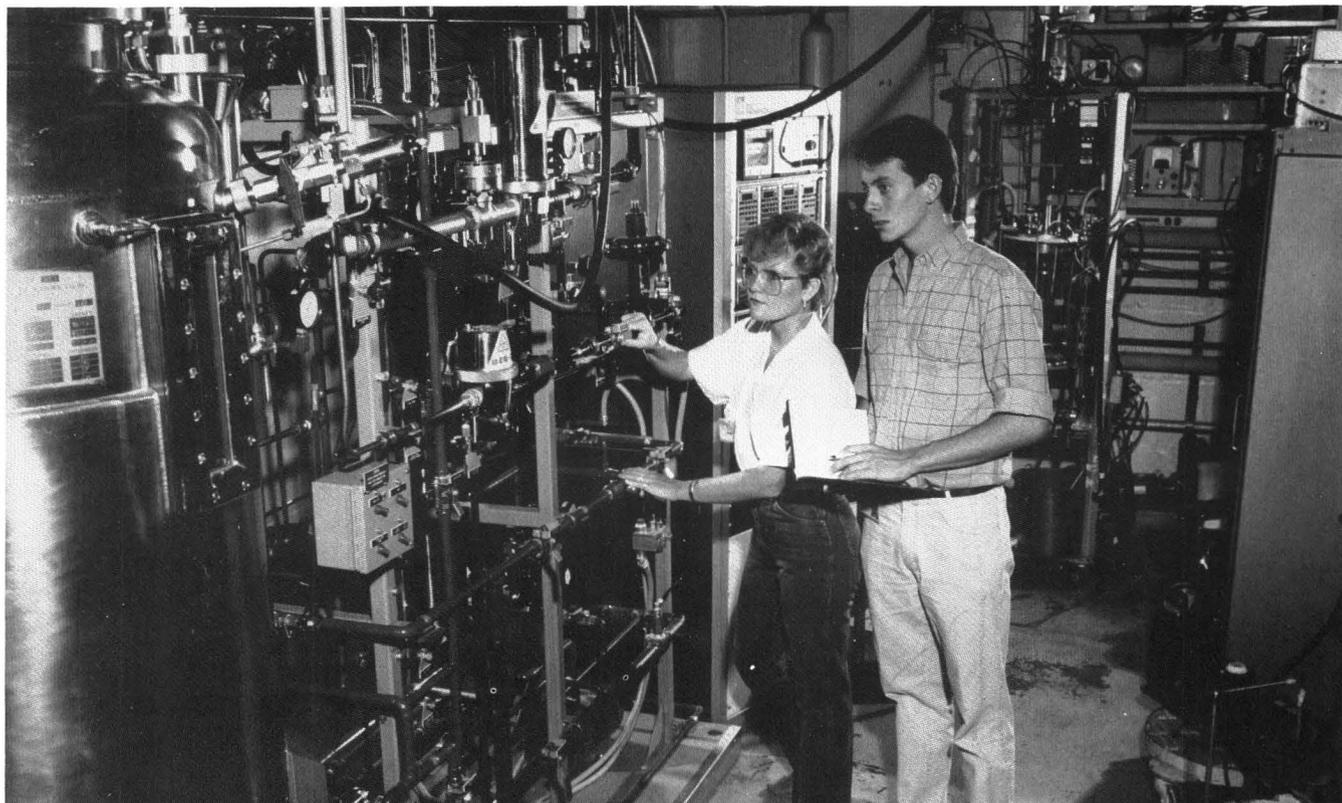
Dr. George C. Martin
Department of Chemical
Engineering and
Materials Science
320 Hinds Hall
Syracuse University
Syracuse, NY 13244
315-423-2559



Kleine Welton (Small Worlds) VII, Wassily Kandinsky,
c. 1922, Syracuse University Art Collection

THE UNIVERSITY OF TENNESSEE, KNOXVILLE

GRADUATE PROGRAMS IN CHEMICAL ENGINEERING



UT Knoxville graduate students Vickie Gilbert and Jim Gambill use one of the 500 liter fermentors in the Biology division of the Oak Ridge National Laboratory for their research on large scale production of genetically engineered DNA.

MAJOR RESEARCH AREAS

BIOPROCESS ENGINEERING

- Center for Environmental Biotechnology
- Bioprocess Research Facility at ORNL

PROCESS CONTROL

- Measurement and Control Engineering Center
- Internships at Tennessee Eastman

POLYMERS

- Center for Materials Processing

COMPUTER-AIDED DESIGN

- Waste Management and Educational Institute

SEPARATIONS AND TRANSPORT

WRITE TO:

**DEPARTMENT OF
CHEMICAL ENGINEERING**
UNIVERSITY OF TENNESSEE
KNOXVILLE, TN 37996-2200

FACULTY AT KNOXVILLE AND OAK RIDGE

P.R. Bienkowski	Bioprocessing, Thermodynamics
D.C. Bogue	Polymers, Rheology
D.D. Bruns	Process Control, Modeling
C.H. Byers ¹	Separations & Transport
E.S. Clark	Polymers
H.C. Cochran ¹	Thermodynamics
R.M. Counce	Separations & Transport
B.H. Davison ¹	Bioprocessing
T.L. Donaldson ¹	Bioprocessing
J.F. Fellers	Polymers
G.C. Frazier	Bioprocessing, Kinetics
J.M. Holmes	Computer-aided Design, Economics
H.W. Hsu	Bioprocessing, Transport
C.F. Moore	Process Control
J.J. Perona (Head)	Separations & Transport, Heat & Mass Transfer
C.D. Scott ¹	Bioprocessing, Separations
T.C. Scott ¹	Bioprocessing, Separations
C.O. Thomas	Computer-aided Design, Economics
T.W. Wang	Process Control, Bioprocessing
J.S. Watson ¹	Separations & Transport, Nuclear Fusion
F.E. Weber	Computer-aided Design, Radiation Chemistry

¹located at the Oak Ridge National Laboratory (ORNL), 20 miles from the main campus at Knoxville

THE UNIVERSITY OF TEXAS AT AUSTIN

RESEARCH INTERESTS

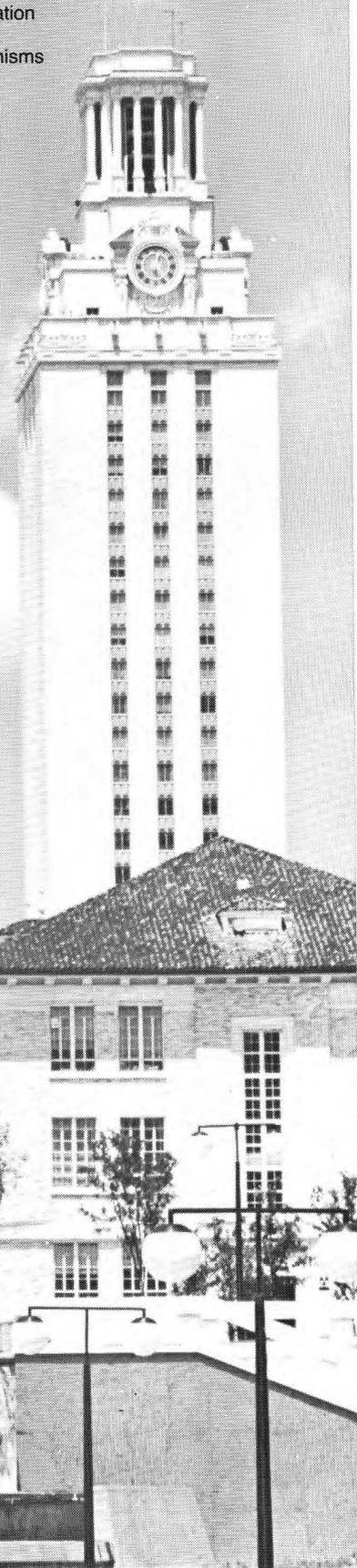
Aerosol Physics & Chemistry	Enhanced Oil Recovery	Process Design & Development
Artificial Internal Organs	Enzyme Production	Process Dynamics & Control
Aqueous Mass Transfer	Fault Detection & Diagnosis	Process Modelling & Simulation
Biochemical Engineering	Heat Transfer	Reaction Injection Molding
Biomedical Engineering	Laser Processing	Reaction Kinetics & Mechanisms
Blood-Contacting Biomaterials	Materials Science	Separation Processes
Catalysis	Membrane Science	Stack Gas Desulfurization
Chemical Engineering Education	Multi-phase Systems	Superconductive Materials
Chemical Vapor Deposition	Optimization	Supercritical Fluid Science
Colloid Science	Plasma Processing	Surface Science
Combustion	Polymer Blends	Thermodynamics
Crystal Structure & Properties	Polymer Processing	Thrombosis
Crystallization	Polymer Thermodynamics	

CHEMICAL ENGINEERING FACULTY

J. W. BARLOW (University of Wisconsin)
J. R. BROCK (University of Wisconsin)
T. F. EDGAR (Princeton University)
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H. STEINFINK (Polytechnic Institute of New York)
J. E. STICE (Illinois Institute of Technology)
I. TRACHTENBERG (Louisiana State University)
E. H. WISSLER (University of Minnesota)

Inquiries should be sent to

Graduate Advisor
Department of Chemical Engineering
The University of Texas
Austin, Texas 78712



Texas A&M

TEXAS A&M UNIVERSITY

The Department of Chemical Engineering at Texas A&M University has an enrollment of about 100 graduate students. All qualified students receive a 12-month appointment and a stipend. Currently the stipends are \$1028 per month for Ph.D. students and \$857 per month for M.S. students. Out-of-state students who receive stipends are exempt from non-resident tuition and pay the same fees as Texas residents.

The department occupies over 40,000 square feet of the Zachry Engineering Center and has research and computer equipment valued at over \$2 million.

Students with B.S. degrees in pure science or mathematics are encouraged to pursue M.S. degrees in Chemical Engineering through our Science Majors Program.

Texas A&M University is located in an area which has a population of over 100,000. It is located 100 miles northwest of Houston, 90 miles east of Austin, and 170 miles south of Dallas. The main campus area is one mile square, with a physical plant valued at about \$639 million.

Admission to Texas A&M University and any of its sponsored programs is open to qualified individuals regardless of race, color, age, religion, sex, national origin or educationally unrelated handicaps.

Faculty and Research Interest

- R. W. Flumerfelt**, Head, Ph.D., Northwestern, 1965 - fluid mechanics, interfacial phenomena
- A. Akgerman**, Ph.D., Virginia, 1971 - reaction engineering, diffusion, waste treatment
- R. G. Anthony**, Ph.D., Texas, 1966 - catalysis, reaction engineering
- D. B. Bukur**, Ph.D., Minnesota, 1974 - reaction engineering, numerical techniques
- J. A. Bullin**, Ph.D., Houston, 1972 - gas sweetening, asphalt characterization
- R. Darby**, Ph.D., Rice, 1962 - rheology, polymers
- R. R. Davison**, Ph.D., Texas A&M, 1962 - methanol fuel, asphalt characterization
- L. D. Durbin**, Ph.D., Rice, 1961 - process control
- P. T. Eubank**, Ph.D., Northwestern, 1961 - thermodynamics
- A. M. Gadalla**, Ph.D., Sheffield (England), 1964 - ceramics, materials science
- C. J. Glover**, Ph.D., Rice, 1975 - polymer solutions
- K. R. Hall**, Ph.D., Oklahoma, 1967 - thermodynamics
- D. T. Hanson**, Ph.D., Minnesota, 1968 - biochemical engineering
- C. D. Holland**, Ph.D., Texas A&M, 1953 - separation processes, distillation, unsteady-state processes
- J. C. Holste**, Ph.D., Iowa State, 1973 - thermodynamics
- M. T. Holtzapple**, Ph.D., Pennsylvania, 1978 - biochemical engineering
- H. A. Preisig**, Ph.D., Swiss Federal Institute of Technology, 1984 - process control
- A. T. Watson**, Ph.D., Cal. Tech., 1979 - porous media, math modeling
- R. E. White**, Ph.D., Univ. of Calif., Berkeley, 1977 - electrochemistry, math modeling

For Additional Information Contact

Graduate Advisor
Department of Chemical Engineering
Texas A&M University
College Station, Texas 77843-3122
(409) 845-3307



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Assistantships and Fellowships available.

CHEMICAL ENGINEERING FACULTY

Gary F. Bennett, Ph.D., University of Michigan. Professor; Environmental Pollution Control, Biochemical Engineering.

Kenneth J. De Witt, Ph.D., Northwestern University. Professor; Transport Phenomena, Mathematical Modeling and Numerical Methods.

Ronald L. Fournier, Ph.D., University of Toledo. Assistant Professor; Transport Phenomena, Thermodynamics, Mathematical Modelling and Biotechnology.

Millard L. Jones, Jr., Ph.D., University of Michigan. Professor; Process Dynamics and Control, Mathematical Modelling and Heat Transfer.

James W. Lacksonen, Ph.D., Ohio State University. Professor; Chemical Reaction Kinetics, Reactor Design, Pulp and Paper Engineering.

Leslie E. Lahti, Ph.D., Carnegie-Mellon University. Professor; Adductive Crystallization, Flue-gas Desulfurization.

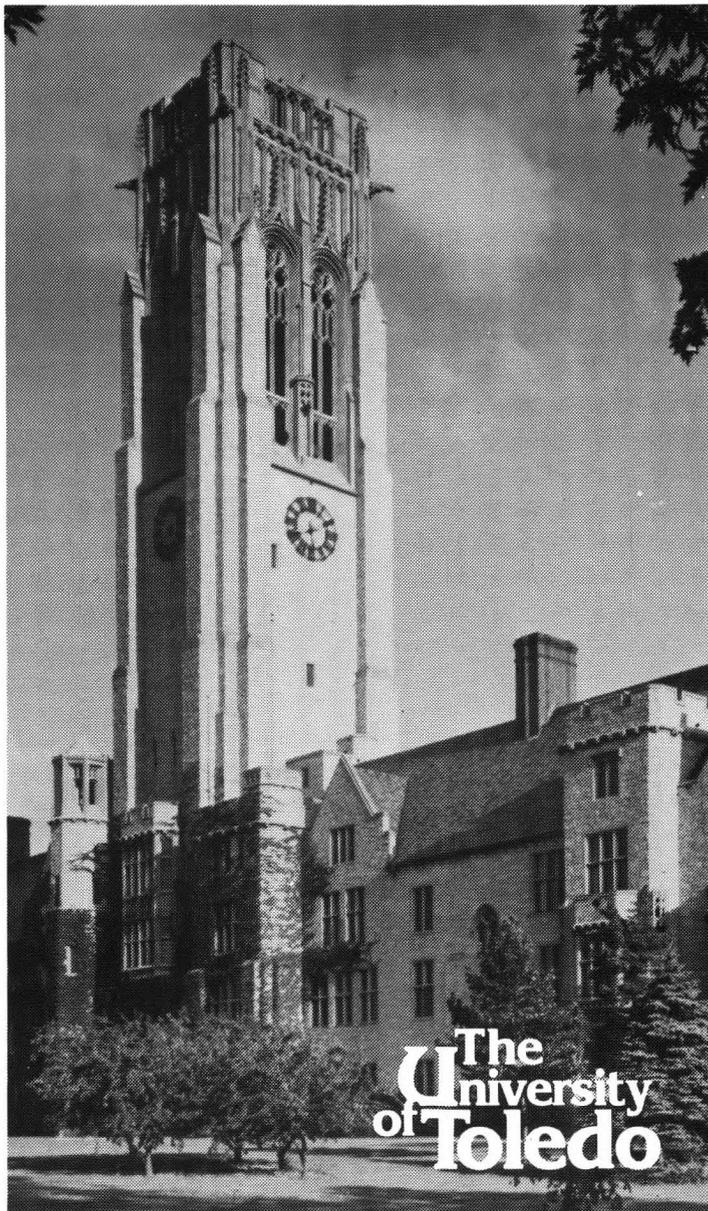
Steven E. LeBlanc, Ph.D., University of Michigan. Assistant Professor; Dissolution Kinetics, Surface and Colloid Phenomena, Controlled Release Technology.

Stephen L. Rosen, Chairman, Ph.D., Cornell University. Professor; Polymeric Materials, Polymerization Kinetics, Rheology.

Sasidhar Varanasi, Ph.D., State University of New York at Buffalo. Assistant Professor; Colloidal and Interfacial Phenomena, Enzyme Kinetics, Membrane Transport.

For Details Contact:

Dr. S. L. Rosen, Chairman
Department of Chemical Engineering
The University of Toledo
Toledo, OH 43606-3390
(419) 537-2639



Regarded as one of the nation's most attractive campuses, The University of Toledo is located in a beautiful residential area of the city approximately seven miles from downtown. The University's main campus occupies more than 200 acres with 40 major buildings. A member of the state university system of Ohio since July 1967, The University of Toledo observed its 100th anniversary as one of the country's major universities in 1972.



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CURRENT RESEARCH AREAS

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MATERIALS AND INTERFACES: Polymers and Fiber Science, Composite Materials, Adhesion at Interfaces, Stability and Rheology of Suspensions, Coal Slurries, VLSI Fabrication

BIOCHEMICAL ENGINEERING: Fermentation Technology, Mammalian Cell Bioreactors, Separation of Biomolecules

KINETICS AND CATALYSIS: Heterogeneous Catalysis, Electrocatalytic Processes

ENVIRONMENTAL ENGINEERING

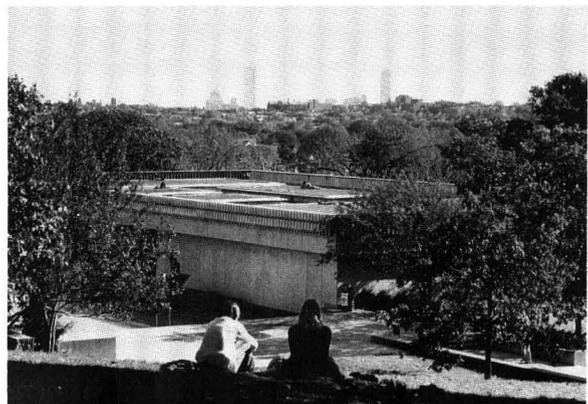
BIOMEDICAL ENGINEERING

THERMODYNAMICS

OPTIMIZATION

FOR INFORMATION AND APPLICATIONS, WRITE:

PROF. GREGORY D. BOTSARIS, CHAIRMAN
DEPARTMENT OF CHEMICAL ENGINEERING
TUFTS UNIVERSITY
MEDFORD, MA 02155



IN METROPOLITAN BOSTON



An aerial view of the campus located on a plateau between the Allegheny and Blue Ridge Mountains.

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At Virginia Tech, we apply chemistry to the needs of man! Study with outstanding professors in the land of Washington, Jefferson, Henry and Lee . . . where Chemical Engineering is an exciting art. Some current areas of major activity are:

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chemical and microbiological processing, chemicals from renewable resources

Catalysis

homogeneous, heterogeneous, spectroscopy, novel immobilizations of homogeneous systems, zeolite synthesis

Fluid-Particle Systems

novel applications of vibrated beds: in heat transfer; in microreactors with rapid, frequent shift in gas atmosphere (for unsteady state kinetic studies); in microreactors that simulate the reaction scene in large-scale gas-fluidized beds (for process development of such beds)

Surface Chemistry

semiconductors, model catalysis, metal oxides, gas sensors, combined high pressure UHV surface analysis

Microcomputers, Digital Electronics, and Control

digital process measurements, microcomputer inter-facing, remote data acquisition, digital controls

Polymer Science and Engineering

processing, morphology, synthesis, surface science, biopolymers

Biotechnology

rheology of large-scale cultures, oxygen mass transfer in large scale cultures, membrane isolation science, hydrophobic interaction chromatography, in situ biodegradation of toxic wastes

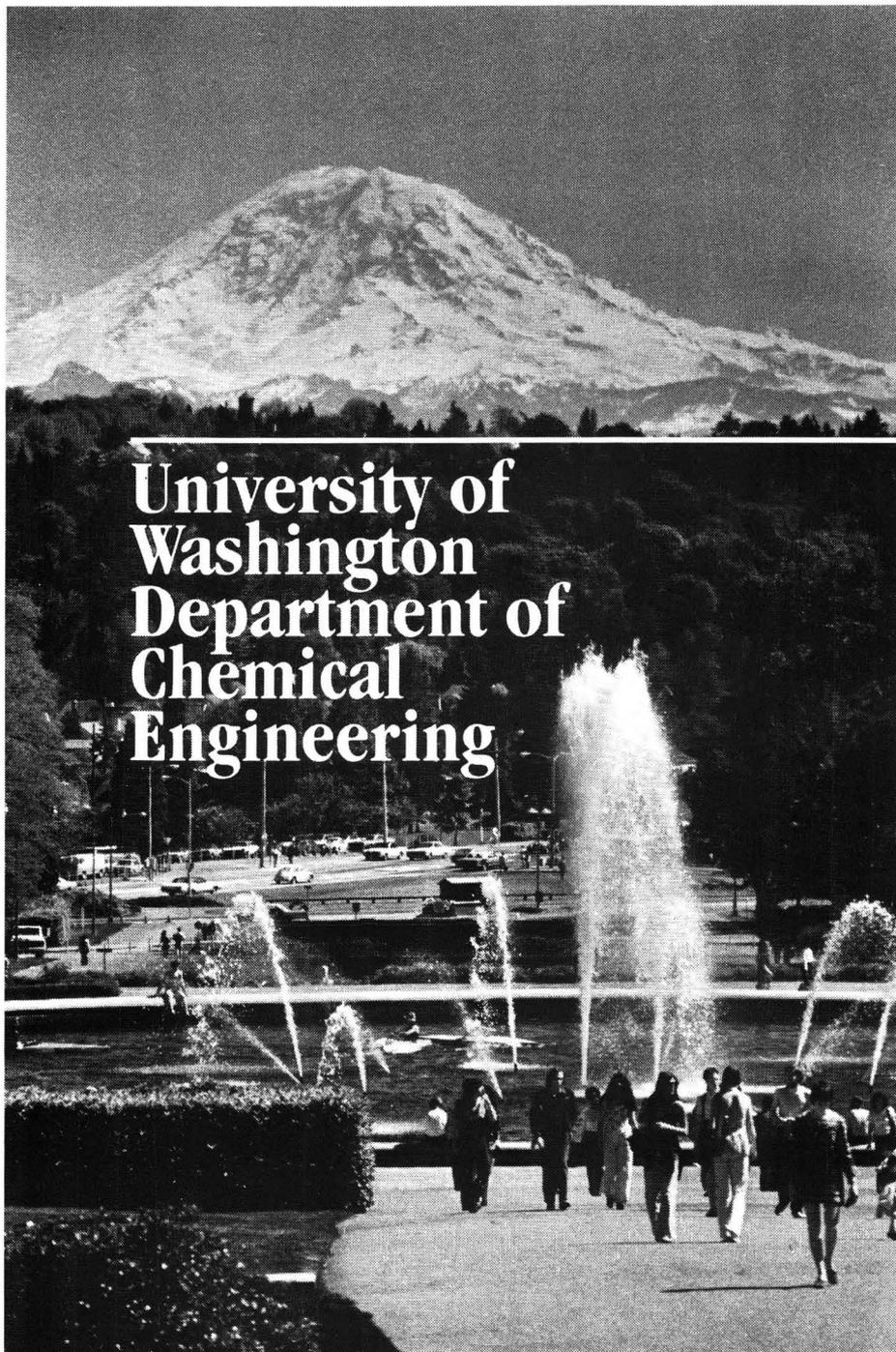
Surface Activity

use of bubbles and other interfaces for separations, water purification, trace elements, concentration, understanding living systems

VPI&SU is the state university of Virginia with 20,000 students and over 5,000 engineering students ... located in the beautiful mountains of southwestern Virginia. White-water canoeing, skiing, backpacking, and the like are all nearby, as are Washington, D.C. and historic Williamsburg.

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Write to: Graduate Committee, Chemical Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061



University of Washington Department of Chemical Engineering

The Department has a vigorous research program and excellent physical facilities. There are about 70 graduate students, of whom typically 10–15 are foreign students and the remainder are from about 30 universities in over 20 states. All full-time graduate students are supported.

The research environment is stimulating and supportive, and there is a fine esprit de corps among the graduate students and faculty. Seattle is a beautiful city with outstanding cultural activities and unparalleled outdoor activities throughout the year.

We welcome your inquiry. For further information please write:

Chairman
Department of Chemical Engineering, BF-10
University of Washington
Seattle, WA 98195

Regular Faculty

J. Ray Bowen, Ph.D., Stanford
(Dean, College of Engineering)
John C. Berg, Ph.D., California (Berkeley)
E. James Davis, Ph.D., Washington
Bruce A. Finlayson, Ph.D., Minnesota
Rod R. Fisher, Ph.D., Iowa State
William J. Heideger, Ph.D., Princeton
Bradley R. Holt, Ph.D., Wisconsin
Eric W. Kaler, Ph.D., Minnesota
Barbara B. Krieger, Ph.D., Wayne State
N. Lawrence Ricker, Ph.D., California
(Berkeley)
James C. Seferis, Ph.D., Delaware
Charles A. Sleicher, Ph.D., Michigan
Eric M. Stuve, Ph.D., Stanford

Research Faculty

Thomas A. Horbett, Ph.D., Washington

Adjunct and Joint Faculty

Active in Department Research

G. Graham Allan, Ph.D., Glasgow
Allan S. Hoffman, Sc.D., M.I.T.
Buddy D. Ratner, Ph.D., Brooklyn Polytechnic

Research Areas

Aerosols
Biochemical and Biomedical Engineering
Colloids and Microemulsions
Fluid Mechanics and Rheology
Heat Transfer
Interfacial Phenomena
Mathematical Modeling
Polymer Science and Engineering
Process Control and Optimization
Pulp and Paper Chemistry and Processes
Reaction Engineering
Surface Science

WASHINGTON STATE UNIVERSITY

Chemical Engineering Department

Here at Washington State University, we are proud of our graduate program, and of our students. The program has been growing quickly in size and quality, but is still small and informal.

For a department of this size, the range of faculty research interests is very broad. Students choose research projects of in-

terest to them, then have the opportunity—and the responsibility—to make an individual contribution.

Through a combination of core courses and many electives, students can gain a thorough understanding of the basics of chemical engineering.

FACULTY AND RESEARCH INTERESTS

J. M. Lee (Ph.D., University of Kentucky): plant tissue cultivation, genetic engineering, enzymatic hydrolysis, mixing.

K. C. Liddell (Ph.D., Iowa State University): semiconductor electrochemistry, reactions on fractal surfaces, separations, radioactive waste management.

R. Mahalingam (Ph.D., University of Newcastle-upon-Tyne): multiphase systems, physical and chemical separations, particulate phoretic phenomena, electronic materials and polymers, synfuels and environment.

R. C. Miller (Ph.D., University of California—Berkeley): chemical/phase equilibria, thermodynamic properties, cryogenics, chemical process engineering.

J. N. Petersen (Ph.D., Iowa State University): adaptive on-line optimization of biochemical processes, adaptive control, drying of food products.

J. C. Sheppard (Ph.D., Washington University): radioactive wastes, actinide element chemistry, atmospheric chemistry, radiocarbon dating.

W. J. Thomson (Ph.D., University of Idaho): kinetics of solid state reactions, sintering rates of ceramic and electronic material precursors, chemical reaction engineering.

B. J. Van Wie (Ph.D., University of Oklahoma): kinetics of mammalian tissue cultivation, bio-reactor design, centrifugal blood cellular separations, development of biochemical sensors.

R. L. Zollars (Ph.D., University of Colorado): multiphase reactor design, polymer reactor design, colloidal phenomena, chemical vapor deposition reactor design.

GRADUATE DEGREE PROGRAMS AT WSU

M.S. in Chemical Engineering

Twelve credits in graduate chemical engineering courses, nine credits in supporting courses, and a thesis are required.

Ph.D. in Chemical Engineering

Eighteen credits in graduate chemical engineering courses, sixteen credits in supporting courses, and a dissertation are required. Upon successful completion of the coursework and the Ph.D. preliminary examination, a student is admitted to candidacy for the degree. The dissertation must represent a significant original contribution to the research literature.

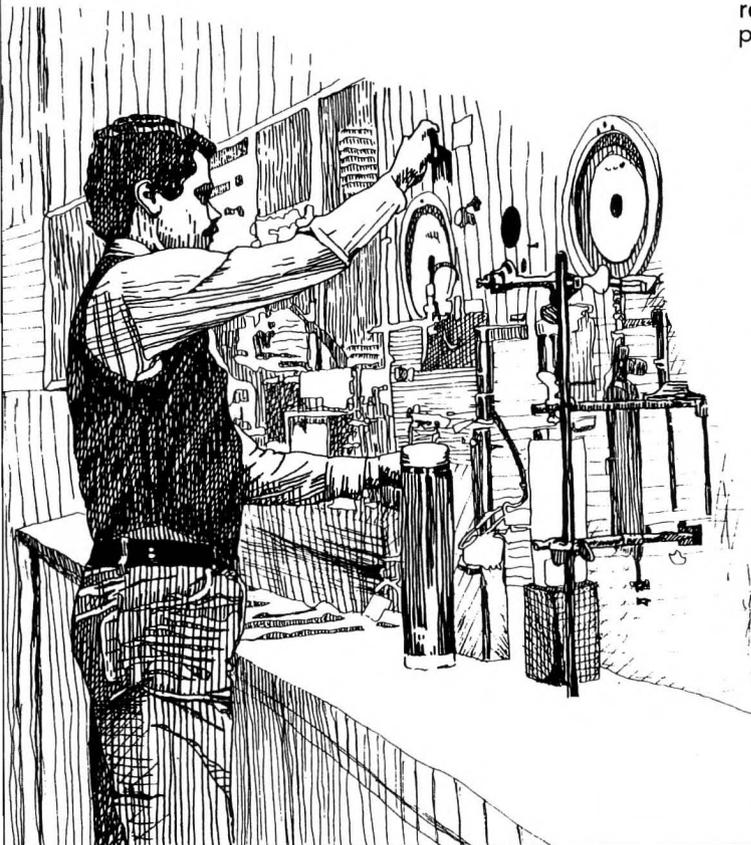
Conversion Program

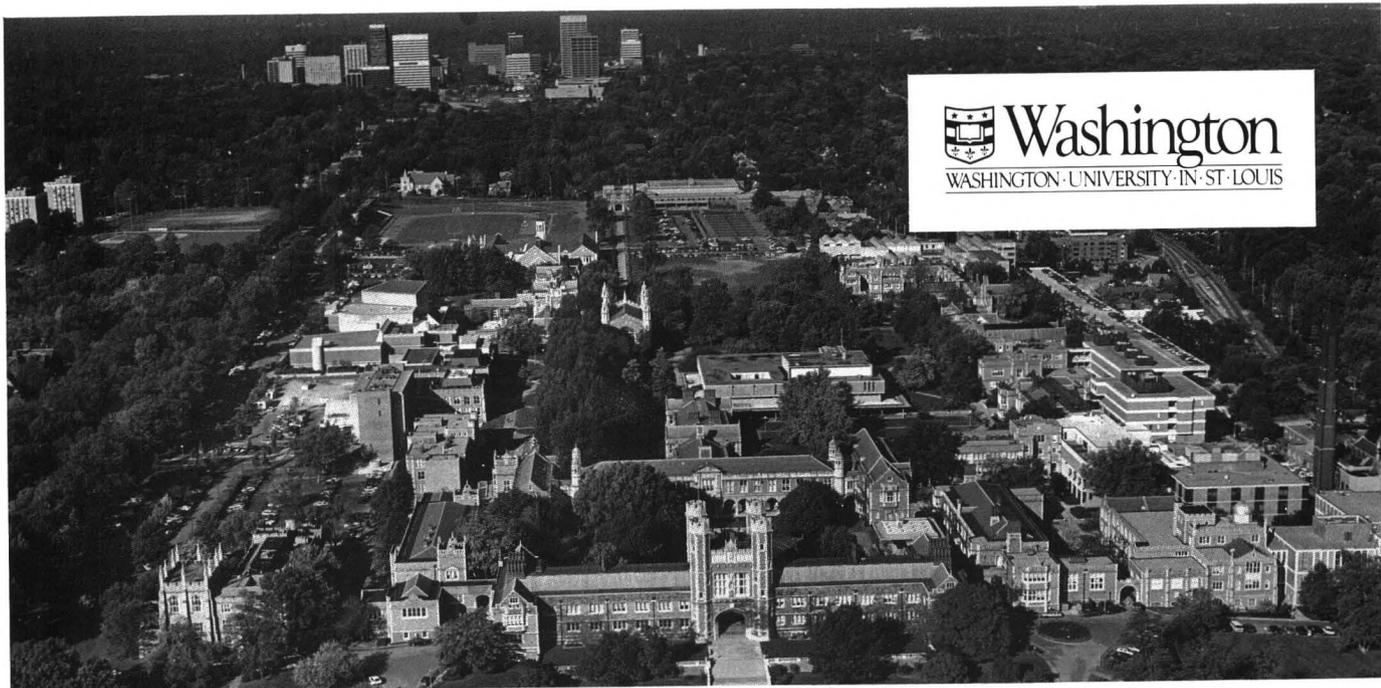
Students with B.S. degrees in the physical or life sciences may apply for admission to the conversion program. Normally a small number of undergraduate courses must be taken in addition to the regular requirements for the M.S. or Ph.D.

FINANCIAL ASSISTANCE

Research or teaching assistantships, partial tuition waivers, and fellowships are available, and nearly all of our students receive financial assistance. Living costs are quite low.

WANT TO APPLY? Contact: Dr. K.C. Liddell, Graduate Coordinator, Department of Chemical Engineering, Washington State University, Pullman, WA 99164-2710, 509/335-4332 or 509/335-3710.






Washington
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GRADUATE STUDY IN
CHEMICAL
ENGINEERING

MASTER'S AND
DOCTORAL PROGRAMS

FACULTY AND
RESEARCH AREAS

M. P. Dudukovic
 Chemical Reaction Engineering

B. Joseph
 Process Control, Process Optimization,
 Expert Systems

J. L. Kardos
 Composite Materials and Polymer Engineering

F. Kargi
 Biotechnology Engineering

J. M. McKelvey
 Polymer Science and Engineering

R. L. Motard
 Computer Aided Process Engineering

P. A. Ramachandran
 Chemical Reaction Engineering

B. D. Smith
 Thermodynamics

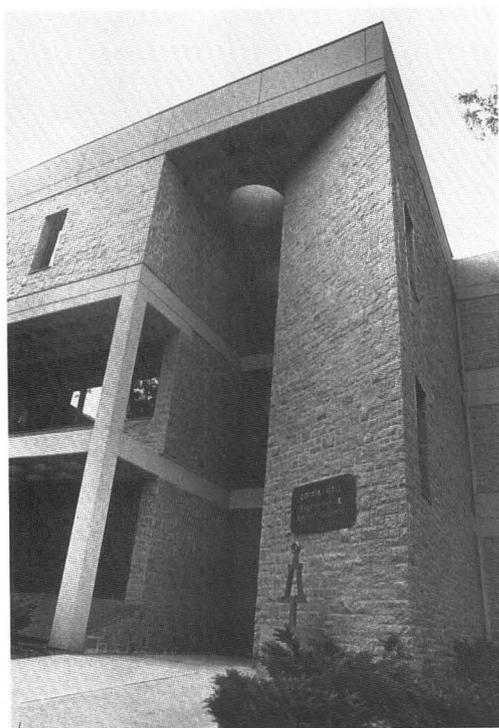
R. E. Sparks
 Biomedical Engineering, Microencapsulation,
 Transport Phenomena

C. Thies
 Transport Phenomena, Microencapsulation

M. Underwood
 Unit Operations, Process Safety,
 Polymer Processing

FOR INFORMATION CONTACT

Graduate Admissions Committee
 Washington University
 Department of Chemical Engineering
 Campus Box 1198
 One Brookings Drive
 St. Louis, Missouri 63130



Washington University encourages and gives full consideration to application for admission and financial aid without respect to sex, race, handicap, color, creed or national origin.



West Virginia University

Chemical Engineering

Faculty

Richard C. Bailie (Iowa State Univ.)
Eugene V. Cilento (Univ. of Cincinnati)
Dady B. Dadyburjor (Univ. of Delaware)
Joseph D. Henry, Jr., Chair. (Univ. of Michigan)
Hisashi O. Kono (Kyushu Univ.)
Joseph A. Shaeiwitz (Carnegie-Mellon Univ.)
Alfred H. Stiller (Univ. of Cincinnati)
Richard Turton (Oregon State)
Wallace B. Whiting (Univ. California, Berkeley)
Ray Y. K. Yang (Princeton Univ.)
John W. Zondlo (Carnegie-Mellon Univ.)

Topics

Catalysis and Reaction Engineering
Separation Processes
Surface and Colloid Phenomena
Phase Equilibria
Fluidization
Biomedical Engineering
Solution Chemistry
Transport Phenomena
Biochemical Engineering
Biological Separations

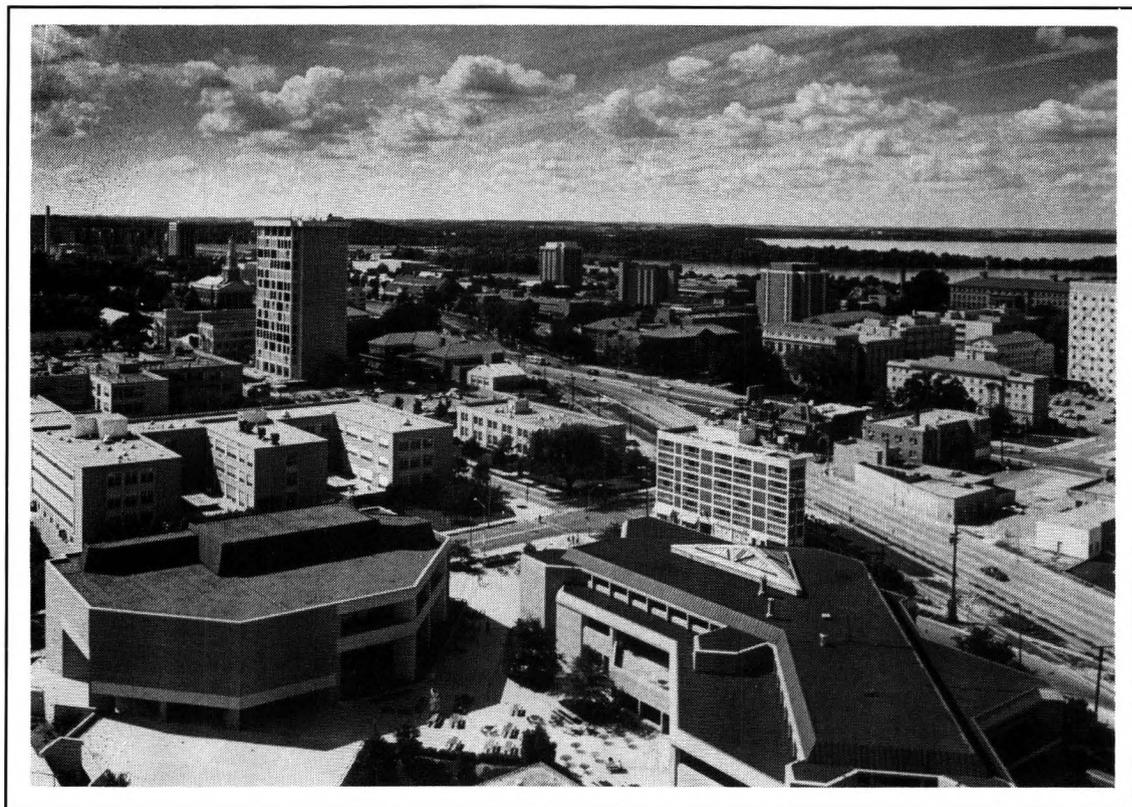
M.S. and Ph.D. Programs

For further information on financial aid write:

Graduate Admission Committee
Department of Chemical Engineering
P.O. Box 6101
West Virginia University
Morgantown, West Virginia 26506-6101

Wisconsin

A tradition of excellence
in Chemical Engineering



Faculty Research Interests

R. Byron Bird:

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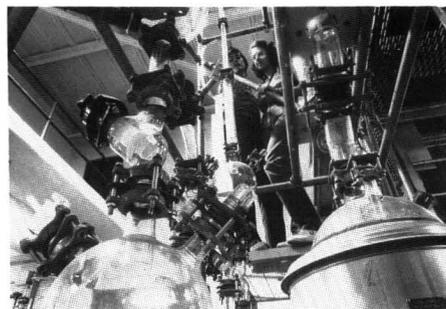
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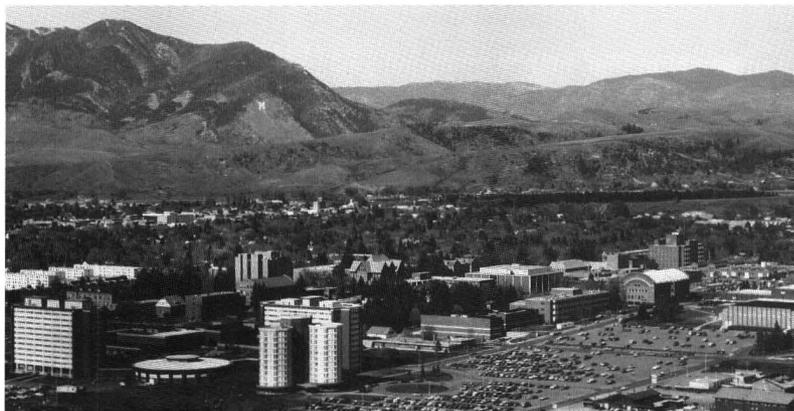
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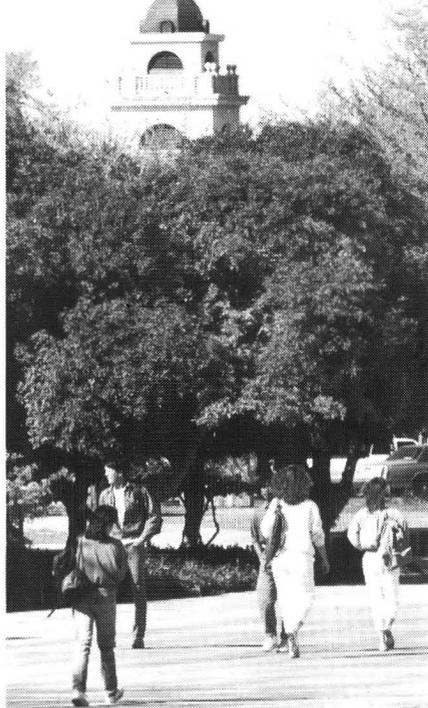
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Graduate Information
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Chemical Engineering at Notre Dame

RESEARCH AREAS

Artificial Intelligence
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Catalysis and Surface Science
Chemical Reaction Engineering
Gas-liquid Flows
Nonlinear Dynamics
Phase Equilibria
Process Dynamics and Control
Statistical Mechanics
Suspension Rheology
Transport Phenomena

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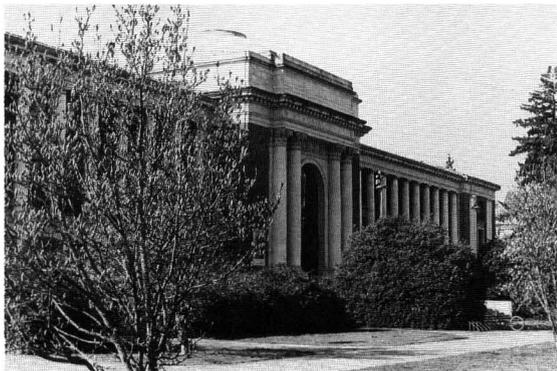
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DEPARTMENT OF
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Physical properties of polymers and composites; adhesion; finite element analysis.

JOE D. GODDARD

(Ph.D., Ch.E., U.C. Berkeley, 1962)
Rheology, continuum mechanics and transport properties of fluids and heterogeneous media.

FRANK J. LOCKHART

(Ph.D., Ch.E., U. of Mich., 1943)
Distillation; air pollution; design of chemical plants (Emeritus).

CORNELIUS J. PINGS

(Ph.D., Ch.E., Caltech, 1955)
Thermodynamics, statistical mechanics and liquid state physics (Provost and Senior Vice Pres., Academic Affairs).

M. SAHIMI

(Ph.D., Ch.E., U. of Minnesota, 1984)
Transport and mechanical properties of disordered systems. Percolation theory and non-equilibrium growth processes. Flow, diffusion, dispersion and reaction in porous media.

RONALD SALOVEY

(Ph.D., Phys. Chem., Harvard, 1958)
Physical chemistry and irradiation of polymers; characterization of elastomers and filled systems; polymer crystallization.

KATHERINE S. SHING

(Ph.D., Ch.E., Cornell U., 1982)
Thermodynamics and statistical mechanics; supercritical extraction.

THEODORE T. TSOTSIS

(Ph.D., Ch.E., U. of Ill., Urbana, 1978)
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Fluid Mechanics

Michel Boudart
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Curtis W. Frank
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Polymer Physics

Gerald G. Fuller
(Ph.D., 1980, Cal Tech)
Fluid Dynamics of Polymeric and Colloidal Liquids

Alice P. Gast
(Ph.D., 1984, Princeton)
Physics of Dispersed Systems

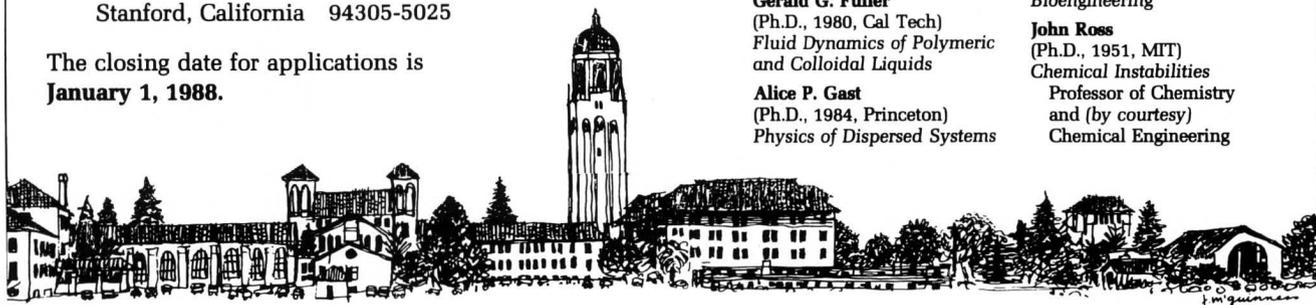
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Robert J. Madix
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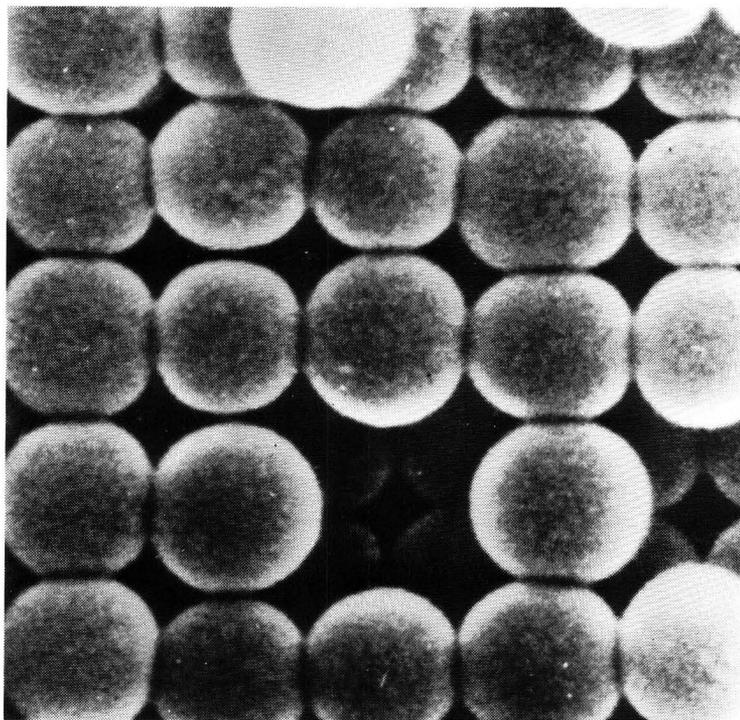
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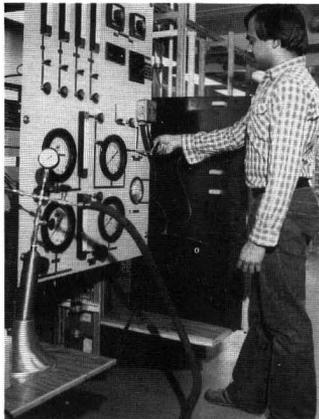
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For information contact

Dr. SST Fan, Chairman
Department of Chemical Engineering
University of New Hampshire
Durham, NH 03824-3591

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MS and MEng. in Chemical Engineering Graduate Studies

PROGRAMS: Thesis and non-thesis options available for MS degree; substantial design component required for M.Eng. program. A full-time student with BSChE can complete program in 9-12 months. Students with degree in chemistry will require two calendar years to complete MS degree.

RESEARCH PROJECTS: Most funded research projects are energy related with the full spectrum of basic to applied projects available. Students participate in project-related thesis problems as project participants.

ENERGY RESEARCH CENTER: A cooperative program of study/research with research projects related to low-rank coal conversion and utilization sponsored by U.S. Department of Energy and private industry is available to limited number of students.

FOR INFORMATION WRITE TO:

**Dr. Thomas C. Owens, Chairman
Chemical Engineering Department
University of North Dakota
Grand Forks, North Dakota 58202
(701-777-4244)**

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Department of Chemical Engineering

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The most active research projects recently have been in heat transfer, process control, reverse osmosis, and surface phenomena. Other topics are available. There is a full-time faculty of eight.

Teaching assistantships are available.

For more information, write

**Robert F. Sweeny, Chairman
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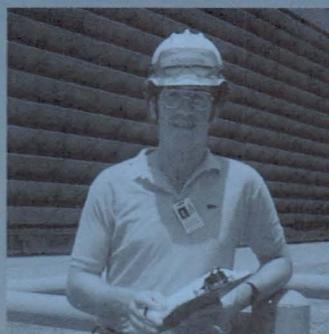
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*For information write to
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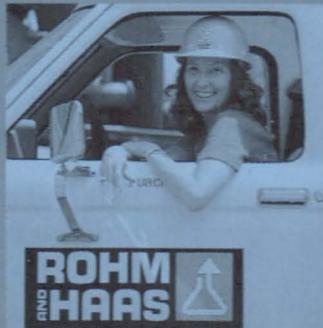
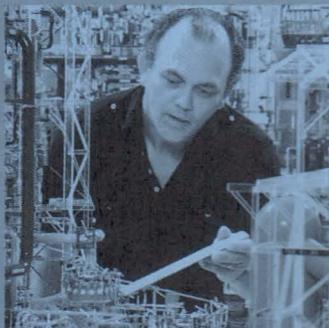
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