GRADUATE EDUCATION ISSUE

Features . . .

An Experiment in Combustion (page 236)
Keith B. Fordon, Antonio M. Vincitore, Selim M. Senkan

Random Thoughts • Impostors Everywhere (page 220)
Richard M. Felder

Combustion Synthesis and Materials Processing (page 228)
Daniel E. Rosner

On the Nature and Conduct of Technical Research (page 222)
John P. O'Connell

Helping Students Become Better Mathematical Modelers (page 254)
Annette L. Bunge, Ronald L. Miller

A Structured Interview for Selection of Graduate Students (page 210)
Marc A. Dubé, Marna Zinatelli

A Novel Laboratory Course on Advanced ChE Experiments (page 260)
J. Lauterbach, S. White, Z. Liu, G.M. Bodner, W.N. Delgass

Toward Technical Understanding: Part 2. Elementary Levels (page 214)
J. M. Haile

Class/Home Problems • Start-Up of a Non-Isothermal CSTR: Mathematical Modeling (page 250)
Aziz M. Abu-Khalaf

Process Integration and Industrial Pollution Prevention:
Merging Theory and Practice in Graduate Education (page 242)

Special Feature • Meet the Authors (page 248)
INDEX
TO
GRADUATE
ADVERTISEMENTS

can be found on

PAGES 266-267.
AWARD LECTURE

202 Synergism Between Research and Teaching in Separations,
Phillip C. Wankat

FEATURES

► 210 A Structured Interview for Selection of Graduate Students,
Marc A. Dubé, Marna Zinatelli

► 214 Toward Technical Understanding: Part 2. Elementary Levels,
J. M. Haile

► 222 On the Nature and Conduct of Technical Research,
John P. O'Connell

► 228 Combustion Synthesis and Materials Processing,
Daniel E. Rosner

► 236 An Experiment in Combustion,
Keith B. Fordon, Antonio M. Vincitore, Selim M. Senkan

► 242 Process Integration and Industrial Pollution Prevention:
Merging Theory and Practice in Graduate Education,
Giorgetto Carta, M. Douglas LeVan, H. Dennis Spriggs,
Gregory A. Cleoteliis II, James E. Ryan, Jr.

► 254 Helping Students Become Better Mathematical Modelers:
Pseudosteady-State Approximations,
Annette L. Bunge, Ronald L. Miller

► 260 A Novel Laboratory Course on Advanced ChE Experiments,
J. Lauterbach, S. White, Z. Liu,
G.M. Bodner, W.N. Delgass

CLASS AND HOME PROBLEMS

250 Start-Up of a Non-Isothermal CSTR: Mathematical Modeling,
Aziz M. Abu-Khalaf

RANDOM THOUGHTS

220 Impostors Everywhere, Richard M. Felder

213 Positions Available

213 Books Received

248 Meet the Authors

249 Book Review

Chemical Engineering Education (ISSN 0009-2479) is published quarterly by the Chemical Engineering Division, American Society for Engineering Education, and is edited at the University of Florida. Correspondence regarding editorial matter, circulation, and changes of address should be sent to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL 32611-6005. Copyright © 1997 by the Chemical Engineering Division, American Society for Engineering Education. The statements and opinions expressed in this periodical are those of the writers and not necessarily those of the CEE Division, ASEE, which hereby assumes no responsibility for them. Defective copies replaced if notified within 120 days of publication. Write for information on subscription costs and for back copy costs and availability. POSTMASTER: Send address changes to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL, 32611-6005. Periodicals Postage Paid at Gainesville, Florida.
SYNERGISM BETWEEN RESEARCH AND TEACHING IN SEPARATIONS

PHILLIP C. WANKAT
Purdue University • West Lafayette, IN 47907-1283

I wish to thank the Chemical Engineering Division of ASEE for this award and the Union Carbide Corporation for its sponsorship of the award. It is a distinct honor to be included among the list of distinguished chemical engineers who have received the division's lecture-ship award.

There is considerable debate about the roles of teaching and research in the University. Astin's extensive survey data shows that on a university-wide basis teaching suffers when major increases in research occur. This appears to be a resource allocation issue. For individual faculty members, the correlation between research and teaching effectiveness appears to be zero or very weakly positive. In any case, these research results rarely get the same public attention as do the muckraking attacks by Sykes, Smith, and others. The voices supporting a balance of teaching and research as the ideal tend to be more moderate and are drowned out. I feel we should continually search for a balance between teaching and research. This paper explores the synergisms between teaching and research that have made my own teaching and research richer and more effective.

In the ideal university, research and teaching are synergistic; the total output is not additive in the sense of \( 2 + 2 = 4 \), but is greater than the sum of the parts, \( 2 + 2 = 5 \), or even 6, 7, or 8. This can come about because of efficiencies in working on both teaching and research—the same effort ends up having multiple uses. And teaching and research provide deeper meaning, each for the other, in unexpected ways. Of course, there are also times when they have little in common, but this does not negate the experience of unity that results when teaching and research synergistically complement each other.
Unlike Gaul, this paper is divided into six parts: since lecturing is used to communicate for both teaching and research, it starts with lecturing; the second part is concerned with people; the next part discusses interactions in learning for both teaching and research; part 4 explores an example of interaction in a graduate-level course; examples of interactions between research and teaching in undergraduate courses appear in part 5; and part 6 asks the question, “Is synergy with service and administrative duties possible?”

PART 1
LECTURING

The most common method of teaching or reporting research results in engineering is lecturing. Any efforts a professor makes to improve lecturing skills will improve both teaching and research lectures. Three things prevent a lecture from being considered terrible:

- Not reading to the audience
- Speaking loudly enough
- Finishing on time

Now, this is easy enough to accomplish and may help explain why only 11% of engineering students rate their instructors as average or below average.

An analysis of learning in college showed that student involvement is needed to obtain learning. This is true in all lectures. Thus, the lecturer must keep the audience engaged and generally paying attention. The positive things that can be done to improve a lecture include the following performance attributes:

- Having a positive attitude
- Showing enthusiasm
- Using visuals
- Making eye contact
- Remembering the attention span is 15 to 20 minutes

The last point is particularly difficult in a research lecture since normally a speaker goes nonstop until the question period. But the norm is wrong. All lectures can benefit from

- Breaks with purposeful audience activity

The purposeful activity helps to involve the audience.

Audience analysis is also useful. Audiences hope that the speaker will

- Keep them awake
- Be somewhat interesting and even funny
- Say something useful to them

If the audience consists of students, they will also want to know

- Will this material be on the test?

Since the research lecture does not have this last motivation, it is even more important to be enthusiastic and humorous.

Note that content plays only a minor role in making a lecture interesting. Practically any content can be made interesting—or boring.

PART 2
PEOPLE

Chemical engineering is a great profession because the people involved in it have developed effective ways of solving important problems. But we often forget the importance of people. It is somewhat traditional in an award lecture to thank people who helped along the way. Without becoming excessively personal, I will briefly discuss some of the people who have influenced me.

My father was an analytical chemist who worked at UOP for forty years. One of his favorite sayings was, “What is your plan B?” I got used to looking for alternatives before things did not work—not bad training for a professor or a department head. Throughout high school I planned to be a chemist, but my father’s advice, “Be a chemical engineer, they’re treated better,” was convincing. My mother’s main contributions were a drive to get things done, which balanced looking for alternatives, and persistence (or stubbornness, depending on one’s viewpoint) in the face of obstacles.

Professor Lowell Koppel taught the mass transfer and separations course when I was an undergraduate. He sparked my interest in distillation and separation and was the best straight (no gimmicks) lecturer I had in my education. Later, when he was my department head, he taught me that one should always challenge the premises first.

Professor Bill Schowalter was my thesis advisor at Princeton, where I did research on hydrodynamic stability analysis. This was an excellent education for research in separations since I learned how to pose problems. The greatest lesson I learned from Bill was to find out why something puzzling or unexpected occurred. One example of this involved solving the quadratic equation $ax^2 + bx + c = 0$ in the middle of a loop in a computer program. The sign of the desired solution would change while the program was running. Why? (The answer can be found at the end of this article after “Closure.”) This lesson to always find out why has proven to be important in both teaching and research.

Professor Jud King’s book, Separation Processes, appeared late in 1970, just as I started to do research and teaching in separations. What a godsend it was! I learned a great deal about separations from it and used it for ten years in an elective course at Purdue. When I spent my first sabbatical at Berkeley, Jud was very supportive of my research efforts in separations at a time when I badly needed support.

On the pedagogy side, two Purdue professor of education had a significant impact on my career. Professor John
Feldhusen’s course, “Educational Psychology for College Teachers,” made me realize that I did not have to copy what I had seen in the classroom. Years later, Frank Oreovicz and I adapted John’s course to engineering and developed a new course, “Educational Methods in Engineering.” Much of John’s course survives in the book Teaching Engineering.[1] Professor Dick Hackney let me take a course in counseling theories despite my obvious lack of preparation. He also encouraged my application to earn an MS in education, and this eventually led to my becoming Head of Freshman Engineering.

Many other people have influenced my teaching and research. They include colleagues, undergraduate students, and graduate students. Hopefully, I have had an equally positive influence on most of them.

On a personal level, in December of 1980 an amazing thing happened. I got married, calmed down, became happier, and found I was much more productive. Then we had children, and I also became responsible. So I want to thank my wife, Dot, and my children, Charles and Jennifer, for enriching my life.

PART 3
LEARNING

There is no better fortune for a professor than to teach and do research in the same area. When I am learning new things about separations, it is not clear if I am doing this for research or for teaching, or for both. They build on each other. Research and teaching are a unified whole with respect to a professor’s learning.

Reading Jud King’s book was my introduction to the countercurrent distribution (CCD) theory of chromatography. This led to including the theory in an elective course on separations. Then I used the theory and did countercurrent distribution experiments for parametric pumping[10] and later for affinity chromatography.[11] The CCD theory has the advantages of being very simple to understand and to program on a computer. The CCD model was used extensively to model chromatography before powerful computers became inexpensive. In CCD all of the mobile phase in a stage is transferred simultaneously to the next stage. Then the mobile and stationary phases in each stage are equilibrated. After equilibration, the mobile phase is again transferred. For linear equilibria, the fraction of the solute in the mobile phase, \( f \), is

\[
f = \frac{K'V_m/V_s}{1 + K'V_m/V_s}
\]

where \( K'(T) = C_m/C_s \) (1)

Then, \( (1-f) \) must be the fraction of solute in the stationary phase. The discrete transfer step combines the stationary phase from stage \( i \) with the mobile phase from the previous stage, \( i-1 \). The mass balance is

\[
M_{i,s} = f_{i-1,s}M_{i-1,s-1} + (1-f_{i-1,s})M_{i-1,s-1}
\]

where \( M_{i,s} \) is the mass of solute in stage \( i \) after transfer step \( s \).

This model results in an equation that is essentially a finite difference form of the more complicated equations needed to describe chromatography with continuous flow. For isothermal chromatography with a pulse input, \( f_{i,s} \) is a constant and an analytical solution of Eqs. (1) and (2) is easily developed.[9]

In parametric pumping the temperature and flow direction are changed periodically. A numerical solution of Eqs. (1) and (2) is easily generated.[10] The results are shown in Figure 1 for extraction parametric pumping. Although the agreement was obviously not good (probably because of evaporation of the diethyl ether), the model was useful since it did not predict the infinite separation factors that linear models for columns did. The same paper[10] included a continuous-flow model for parametric pumping. The development of that model occupied over two pages in the journal, compared to less than half a page for the discrete-transfer model. A number of other researchers subsequently used both discrete transfer and continuous-flow models to model parametric pumping and other cyclic separations.

This success with a chromatographic theory led me to take a chromatography course from Professor Buck Rogers in chemistry. Buck encouraged me to become more involved in chromatography research. I used the CCD theory to explain affinity chromatography.[11] The affinity chromatography research made it abundantly clear that biochemistry was needed, so I took two biochemistry courses, which helped further research in biochemical separations.[12] About this time I became cocky and thought I knew enough adsorption and chromatography to develop a graduate-level elective on adsorption and chromatography. Since the teacher invariably

Figure 1. Comparison of theoretical and experimental results for discrete transfer test tube parametric pumping system. Diethyl ether stationary phase, water moving phase, acetic acid solute. Theoretical results correspond to: \( f_i=0.515; f_s=0.476; V_e=V_h=0; 5 \) stages, 2 transfers per half-cycle.

(Reprinted with permission from Wankat, Copyright 1973, American Chemical Society.)
learns more than the students, I had to really learn the different theories of adsorption and chromatography. I spent a great amount of time studying Chapter 10 of Sherwood, Pigford, and Wilke[13] and reading the literature.

The students in this graduate separations elective voted to learn about membranes. Building on what is included in King’s book, membranes were included in the course. This knowledge eventually became useful in research[14,15] and later became two chapters in the textbook. This pattern of building on learning done for teaching to do research and then building on the knowledge gained in research to improve teaching repeats over and over again.

The knowledge of adsorption and chromatography solutions and mass transfer that I had learned while preparing to teach unexpectedly proved very useful in developing intensification procedures for adsorption,[16] elution chromatography,[17] and PSA.[16,18] The first stages of this research were done during my second sabbatical, spent at ENSIC in Nancy, France. I decided to take the time to answer a question that had nagged me for several years. In analytical liquid chromatography, the use of smaller and smaller packings had revolutionized the method and resulted in HPLC. Yet this development had no impact on adsorption operations and very little impact on large-scale chromatography, both of which have very similar mass transfer characteristics to analytical liquid chromatography. The typical answer to why small particles were not used was that pressure drop would be too large, but I was not convinced. Since I was on sabbatical, I could afford to “waste” my time to look at this question.

In one afternoon a “back-of-the-envelope” calculation convinced me that the common wisdom, based on a constrained optimization, was wrong. For example, Sherwood, Pigford, and Wilke show diminishing returns as the particle diameter decreases. But in their example, the cycle time was set constant at ten minutes. A reworking of this example[16] clearly shows that there is an advantage to reducing particle diameter if the cycle time and column length are scaled correctly.

The initial analysis was rather approximate and the next ones were a bit on the messy side. Eventually, simpler ways of solving the problem, such as the dimensionless analysis employed to analyze pressure swing adsorption (PSA),[18] were developed. This work actually used what I had learned about dimensionless analysis in my PhD thesis on hydrodynamic stability analysis, and thus it illustrates that problem-solving techniques are often transferable to very different problems. By the time this material was included in a textbook,[15] the theory had been simplified significantly. The following development is based on the textbook presentation, but can easily be extended for more complex cases. The textbook presentation takes us full circle since the results of the research are now being taught to students.

Assume that we have an adsorption column that works satisfactorily. It does not matter how this “old” design was developed. We now wish to develop a “new” design. By taking ratios of the controlling equations, we can do the new design without solving any differential equations. The pressure drop in a packed bed of rigid particles with laminar flow is

$$\Delta p = \frac{\mu v e}{K d_p}$$  \hspace{1cm} (3)

where $K$ is the bed permeability that depends only on the porosity. Taking the ratio of Eq. (3) for the old and new designs, we obtain

$$\frac{1}{R_p} = \frac{\Delta p_{old}}{\Delta p_{new}} = \left( \frac{v_{old}}{v_{new}} \right) \left( \frac{L_{old}}{L_{new}} \right)^2 \left( \frac{d_{p,new}}{d_{p,old}} \right)^2$$  \hspace{1cm} (4)

The bed porosity for rigid spheres is independent of bed diameter, bed length, and particle diameter; therefore, to a first approximation $K$ cancels out in the derivation of Eq. (4). The interstitial velocity $v$ is related to the volumetric flow rate $Q$ by

$$v = \frac{4Q}{\pi D^2 \varepsilon}$$  \hspace{1cm} (5)

The ratio of old and new velocities is easily obtained and substituted into Eq. (4) to obtain

$$\frac{1}{R_p} = \left( \frac{Q_{new}}{Q_{old}} \right) \left( \frac{D_{new}}{D_{old}} \right)^2 \left( \frac{L_{old}}{L_{new}} \right) \left( \frac{d_{p,new}}{d_{p,old}} \right)^2$$  \hspace{1cm} (6)

If $R_p = 1.0$, then the pressure drops in the old and new designs are equal even though the designs may look very different.

To consider the separation that is achieved, we define

$$\frac{1}{R_N} = \left( \frac{L_{MTZ}}{L_{MTZ,new}} \right)_{old}$$  \hspace{1cm} (7)

where $L_{MTZ}$ is the length of the mass transfer zone. If $R_N = 1.0$, the fractional bed use in the two designs is identical and the separation is identical. (For linear chromatography, $R_N$ is defined as the ratio of the number of plates in the new and old designs.[17]) Substituting the expression for $L_{MTZ}$ for a Langmuir isotherm into Eq. (7), we obtain

$$\frac{1}{R_N} = \left( \frac{Q_{new}}{Q_{old}} \right) \left( \frac{D_{new}}{D_{old}} \right)^2 \left( \frac{L_{old}}{L_{new}} \right) \left( \frac{k_{m,new}}{k_{m,old}} \right) \left( \frac{d_{p,new}}{d_{p,old}} \right)^2$$  \hspace{1cm} (8)

This simplifies if pore diffusion controls to

$$\frac{1}{R_N} = \left( \frac{Q_{new}}{Q_{old}} \right) \left( \frac{D_{new}}{D_{old}} \right)^2 \left( \frac{L_{old}}{L_{new}} \right) \left( \frac{d_{p,new}}{d_{p,old}} \right)^2$$  \hspace{1cm} (9)

When pore diffusion controls, Eqs. (6) and (9) relate the six variables $R_p$, $R_N$, $(Q_{new}/Q_{old})$, $(D_{new}/D_{old})$, $(L_{new}/L_{old})$, and $(d_{p,new}/d_{p,old})$. Four of these are selected as known and the other two are solved for. Since all of the “old” parameters are known

Fall 1997
from the old design, the new parameters are easily determined from the ratios.

If the only significance of this were scale up, the procedure would not have had much impact. The significance on economics is easily seen from a numerical example. If we set \( R_P = 1 \), \( R_N = 1 \), \( (Q_{new}/Q_{old}) = 1 \), and \( (d_{p, new}/d_{p, old}) = 0.1 \), we find that solution of Eqs. (6) and (9) gives \( (L_{new}/L_{old}) = 0.01 \) and \( (D_{new}/D_{old}) = 1 \). To keep the same boundary conditions (or the same relative amount of time processing feed), we must cycle more quickly. For the case considered here, the cycle and feed times must be scaled as

\[
\frac{t_{cycle, new}}{t_{cycle, old}} = \frac{L_{new}}{L_{old}}
\]

which is a ratio of cycle times of 0.01. Thus, a very short column cycling rapidly can produce exactly the same separation with the same pressure drop for the same volumetric flow rate of feed if we reduce the particle diameter. Since the adsorbent volume is \( \pi D^2 L/4 \), this is a much smaller column. If the ratio \( (d_{p, new}/d_{p, old}) \) is a significant change, the new system will need to be redesigned to reduce dead volume. Different geometries such as annular flow may become viable. Now that I am finished with this research, it has caught the attention of companies that separate gases by adsorption.

**PART 4**

**GRADUATE STUDENT PROJECTS IN COURSES**

One would expect that graduate students would do a significant amount of research for their theses, and, of course, doing this research involves learning how to do research. By working with the students, the professor helps the students learn—which is not a bad definition of teaching. Thus, teaching and research are synergistic during normal graduate student research. Synergism can also occur between research and graduate students’ projects in courses.

Several graduate-student projects in courses have eventually resulted in papers. For example, Narsi Sundaram, a student in my advanced separations course, decided he wanted to look at PSA for his course project. After a bit of searching, he decided to look at the effect of pressure drop on the repressurization and blowdown steps in PSA. I "knew" that this effect would be negligible, but since a negative result is perfectly acceptable for a project, I gave him the go-ahead. He found

---

**Figure 2.** (a) Two-enthalpy feed analog of ordinary flash distillation—column-flash distillation. (b) Column-flash distillation: \( N=5 \) equilibrium stages, \( q=0.5 \), \( \alpha=5 \), \( x_p=0.5 \), constant molal overflow. (c) Column-flash and ordinary flash distillation: McCabe-Thiele analysis, \( N=1 \) equilibrium stage, \( q=0.5 \), \( \alpha=5 \), \( x_p=0.5 \). (d) Effect of \( q=F_1/(F_1+2F_2) \) and \( N \) on separation of ethanol from water using a column-flash system. Results of Aspen Plus simulations. Equilibrium data used physical property package SYSOP18. Feed is 10 mol % water. Pressure=1 atm. From left to right in each series of seven points for a given \( N \): \( LV=F_1/F_2=0.25 \), 0.50, 0.75, 1.00, 2.00, 3.00, 4.00. (Reprinted with permission from Wankat and Kessler [24], Copyright 1993, American Chemical Society.)

---
that under certain conditions the effect of pressure drop was much larger than anyone expected. Narsi switched his thesis topic to work with me on this in more detail, and eventually we published the result. \[20\] This paper led to an outpouring of other papers on the topic (unfortunately, not by me), and at least one of the major gas companies changed their computer modeling to include this effect. So, what do I know?

If space allowed, there are other examples we could explore in depth. In all cases, additional work was necessary to take the original student project and make it publishable. This type of synergism between teaching and research is relatively obvious.

**PART 5**

**INTERACTION WITH UNDERGRADUATE COURSES**

To this point, the synergisms between research and teaching have involved graduate-level courses or senior electives. There are synergisms between teaching required undergraduate courses and research, but they are fewer.

I first became interested in distillation as a junior at Purdue. I found the McCabe-Thiele diagram to be fascinating. I wanted to do research on distillation, but for many years couldn't seem to find an opening. Instead, I taught the junior-level equilibrium staged course at Purdue for many years and eventually wrote a textbook for the course.\[21\] Finally, during a 1992 sabbatical at the University of Florida, I started some distillation research. (Funny how these things seem to happen on sabbatical.) I had developed a new PSA process that used the feed gas for a partial purge.\[22\] During the hunt for other possible uses of this idea, I remembered that Suzuki\[23\] had shown that PSA and distillation were analogous. (Actually, Suzuki wrote that PSA can be approximately analyzed as a continuous countercurrent process.) With this (inaccurate) analogy, the column flash distillation system shown in Figure 2a\[24\] was developed. At first glance, it does not look like distillation since there is no reboiler and no condenser. But years of teaching that distillation is a vapor-liquid separation system with heat as the separation agent had convinced me that neither a reboiler nor a condenser is needed. Figure 2a is a form of distillation. The operating line and the McCabe-Thiele diagram are shown in Figure 2b. If there is a single stage, the result becomes the same as normal flash distillation (Figures 2c). The results of more detailed simulations done with Aspen are shown in Figure 2d. They show that column flash can achieve more separation than a normal flash.

This was interesting, but not necessarily useful. So Dave Kessler and I extended the idea to distillation columns. The eventual result was the two-feed column shown in Figure 3a.\[24\] A comparison of the McCabe-Thiele diagrams for the single-feed operation (Figure 3b) to the two feed-system (Figure 3c) shows that when the single-feed system would be a
two-phase feed, the two-feed column is significantly better. What is meant by "better" is illustrated in Figures 4a, 4b, and 4c, which are results of Aspen simulations.

After the research was done and while Dave and I were writing the paper, I realized I had seen this type of two-feed distillation before. It is homework problem 6D15 in my distillation textbook.\textsuperscript{[21]} Perhaps there was a subconscious memory that guided the research. While the paper was in the galley-proof state, Dave Manley at the University of Missouri-Rolla informed me that several variants of column flash distillation are covered by U.S. patent 4,726,826 (1988).

My next step will be to incorporate these results in the junior distillation course in the fall of '97. The column flash system will make an excellent test or homework problem. There are also enriching and stripping column examples in the paper\textsuperscript{[24]} that will make novel problems for the students. My experience using Aspen for research will be helpful in using Aspen in the course.

What if you teach courses that are not in your research area? Are there still possible synergisms between teaching and research? What if you teach mass and energy balances? I admit that finding ties between a mass and energy balance course and research may be difficult. After a twenty-two year hiatus, I had the opportunity to teach the mass and energy balance course in the spring of 1997. I used the little red bible\textsuperscript{[25]} as the text. The material was essentially the same as it had been twenty-two years ago, but the students had changed. Going back and reviewing the fundamentals with a different textbook did bring an increased depth to my understanding—I saw an analogy between the choice of reference states for energy balances with a heat of mixing and energy balances for adsorbers with a heat of adsorption. This understanding was helpful in current adsorption modeling research.

Another type of synergy occurred in teaching the mass and energy balance course. This was a synergy between teaching different areas. After about a fourth of the semester, I knew the course was not going well—many students were not learning. Leaning heavily on what I had written\textsuperscript{[2]} and taught about how to teach, I asked the students to write down what they thought would help them learn on a 3x5 card. Using these comments as a guide, I reorganized the remainder of the course. The course improved and the end-of-semester student evaluations were quite positive.

**FIGURE 4.** (a) Effect on reflux ratio of using two-enthalpy feed rather than two-phase feed for $x_F = 0.99, x_B = 0.01, q = 0.5$. (b) Effect on cooling requirements of using two-enthalpy feed rather than two-phase feed for $x_F = 0.99, x_B = 0.01, q = 0.5$. (c) Effect on heating requirements of using two-enthalpy feed rather than two-phase feed for $x_F = 0.99, x_B = 0.01, q = 0.5$.

(Reprinted with permission from Wankat and Kessler,\textsuperscript{[24]} Copyright 1993, American Chemical Society.)

while serving on committees or as an administrator. There are often mutual research or teaching interests that can blossom into collaborations or even funding. This is particularly true of professional service in organizations such as to ASEE or AIChE.

A second benefit, particularly of administrative positions, is the acquisition of a much broader outlook. My experience as Head of Freshman Engineering was extremely useful when I was writing *Teaching Engineering*.\textsuperscript{[22]} Contact with students and professors helped me see the similarities and

**PART 6**

**SERVICE AND ADMINISTRATION**

I considered adding "service" to the title of this paper, but I did not want to lose my credibility at the outset. Although it often seems like a black hole for effort, service and administrative positions can occasionally interact synergistically with research and teaching. Probably the main synergism is the people both inside and outside the university who one meets
differences in teaching engineering in the different engineering disciplines. This helped make Teaching Engineering a book for all engineering professors, not just for chemical engineering professors.

These examples within the university may seem farfetched. Serving as a journal editor, on the other hand, is normally directly related to one's own research. An editor who reads manuscripts in order to make editorial decisions is forced to keep up with the literature in his or her broad area of research. Without this extra incentive, I would read only the literature in my narrow area of specialization. My duties as an associate editor of Chemical Engineering Education have forced me to read and sometimes understand advances in chemical engineering outside of what I usually teach or research.

CLOSURE

Although teaching and research are often viewed as opposites, they often interact synergistically. Efforts to improve as a lecturer will at the same time improve both teaching lectures and research presentations. Learning because one needs to know something for classroom teaching or for research can be both effective and efficient. Once learned, the knowledge is available for unexpected uses in research or teaching. Learning appears to be the major synergistic mechanism between teaching and research. Synergisms do occur between course teaching and research. The most obvious of these are when course projects blossom into research projects. Research results are often, quite deliberately, translated into a form that can be taught to graduate or undergraduate students.

**NOMENCLATURE**

- \( a_p \): surface area/volume of adsorbent, \( m^2/m^3 \)
- \( C_p \): concentration in mobile phase, \( kg/m^3 \)
- \( C_s \): concentration in stationary phase, \( kg/m^3 \)
- \( d_p \): particle diameter, \( m \)
- \( D \): column diameter, \( m \)
- \( f \): fraction of solute in mobile phase, Eq. (1)
- \( i \): index for stage
- \( k_m \): lumped parameter mass transfer coefficient, \( m/s \)
- \( K \): permeability in Eq. (3)
- \( K' \): equilibrium constant, Eq. (1)
- \( L \): column length, \( m \)
- \( L_{MTZ} \): length of mass transfer zone in column, \( m \)
- \( M \): mass of solute in stage, \( kg \)
- \( p \): pressure, \( N/m^2 \)
- \( Q \): volumetric flow rate, \( m^3/s \)
- \( R_N \): ratio of \( L/L_{MTZ} \) in new and old design, Eq. (7)
- \( R_p \): ratio of \( d_p \) in new and old designs, Eq. (4)
- \( s \): index for transfer step
- \( t \): time, \( s \)
- \( T \): temperature, \( ^\circ C \)
- \( v \): interstitial velocity in column, \( m/s \)
- \( V_m \): volume of mobile phase in stage, \( m^3 \)
- \( V_s \): volume of stationary phase in stage, \( m^3 \)
- \( \varepsilon_c \): external porosity
- \( \mu \): viscosity, poise

**REFERENCES**

A STRUCTURED INTERVIEW FOR SELECTION OF GRADUATE STUDENTS

MARC A. DUBE, MARNA ZINATELLI
University of Ottawa • Ottawa, Ontario, Canada KIN 6N5

In this article we will present a method for improving the traditional approach to selecting potential graduate students. The goal of the method is to apply more equitable strategies and reduce the chances of rejecting the “right” students. The method, known as the “structured interview,” is currently used by industrial/organization psychologists to select employees for many major corporations. Although some may question the notion that student selection is an educational issue, we feel strongly that a commitment to the fairest possible selection method models and teaches integrity to students.

New faculty members are often advised by their peers, mentors, and former supervisors to carefully select graduate students who are best suited to the member’s specific field and setting. In fact, it is often said that the choice of graduate students in the early stages of a career heavily influences one’s long-term success as well as that of the students in question. In some settings, selection is done at the departmental level. In such cases, the method described here can be easily adjusted to meet departmental selection needs.

A number of professors were interviewed regarding the secret of their success in recruiting successful graduate students. Recommendations included using criteria such as good marks, high ambition, and good interpersonal skills—and even good luck was cited. Although the responses served to describe successful graduate students, they did not offer a systematic approach to differentiating between applicants. This is an especially difficult task considering the limited amount of time generally devoted to screening applications for graduate studies. Unfortunately, many professors confess that the selection of quality graduate students is basically a “crap shoot.”

One of the most widely used tools for selecting graduate students is the interview. It serves two purposes: to select graduate students and to sell the professor’s (or the department’s) research program to the student. A traditional interview usually consists of an interviewer engaging in a “free-wheeling” conversation with the student. This is known by experts in the field of industrial/organizational psychology as an “unstructured” interview. Although interviewers tend to rely on a set of questions commonly used by their colleagues.

This traditional approach to conducting an interview often results in hiring the best interviewee rather than the best candidate. In fact, recent research findings indicate that this approach has only a 15 to 20% chance of predicting performance. This is particularly unfortunate because it is difficult and costly within the structure of most graduate programs to have unsuccessful students withdraw. Table 1 compares research findings concerning the ability of various selection tools to predict job performance.
The interview procedure discussed here can be somewhat lengthy, but when one expects to work with the candidate for a period that can span two to six or more years, it makes sense to spend a reasonable amount of time on the selection process. . . . It appears worthwhile to invest energy in developing strategies for selection that incorporate the latest available expertise.

Because most questioners tend to ask the candidate to evaluate themselves (e.g., “What are your weaknesses?”), a skillful interviewee can turn an interview into a pleasant, yet uninformative, session. The result is that an interviewee who is well-versed in interviews may well be considered for a position over a poor interviewee who has the potential to become an excellent graduate researcher.

Traditional unstructured interviews also suffer from the fact that they contain no systematic rating procedure. Typically, the interviewer makes a decision based on a “gut feeling” or a “hunch.” In fact, interviewers tend to make a decision about an applicant within the first four or five minutes of the interview. In other words, the first impression made by a prospective candidate turns out to be extremely important. This is troubling since the first few minutes of an interview are typically devoted to idle banter that serves to put the candidate at ease. Research has also identified the following characteristics of unstructured interviews:

- Interview ratings are more influenced by unfavorable information than by favorable information.
- Interviewers recall information presented at the beginning and at the end of an interview better than information in the middle.
- Interview ratings are better if the applicant follows a poor candidate and worse if the applicant follows a good candidate.
- Interviewers see female applicants as more appropriate for certain positions (regardless of qualifications).
- Interviewers give better ratings to applicants with whom they have more in common.

THE STRUCTURED INTERVIEW

One solution to the above problems is the “structured” interview. The use of a structured interview forces the interviewer to avoid straying from a predetermined question sheet and avoids the use of non-job-related questions (such as marital status, age, child care, or religion) that can result in litigation. In fact, precedents have already been set in which structured interviews have protected interviewers from litigation. What many fail to realize is that interviews are viewed by the courts as tests, and as such they are subject to the same validation requirements.

A structured interview is characterized by four basic features: a series of questions relevant to the job, immediate scoring of the answers to the questions, scoring based on benchmark answers, and the calculation of a sum for an overall interview score. Comparisons can be made to a benchmark overall interview score or between competing candidates.

The development of the structured interview is straightforward and has been outlined by Wiesner. First, one must identify examples of effective, ineffective, and typical behaviors that contribute to the success or failure of graduate students. It is generally advisable to draw upon the experience and expertise of several qualified individuals to accomplish this task in order to justify the choice of behaviors.

In our case, extensive consultation with peers and senior colleagues was undertaken first. After establishing a list of qualities (see Table 2), a set of questions was generated to assess the degree to which each candidate possessed the qualities. The questions were designed to reflect typical work situations and to reveal the presence or absence of the quality in question. Benchmark answers and scores were then generated for each question, and the predetermined answers and scores were used to evaluate candidate responses. At the conclusion of the interview, the scores were tabulated. They can be compared either to competing candidates or to a previously established “cut-off” score.
Certain qualities, such as laboratory and computer skills, can be rather difficult to assess by means of a question-and-answer session. In these cases, a simple situational assessment\(^\text{(23)}\) is performed, e.g., the candidate is asked to actually perform the skill being evaluated as part of the interview process.

Using recommendations from the literature,\(^\text{(1-4)}\) we have designed a structured interview for selecting candidates for graduate school in chemical engineering. The interview is based on the qualities associated with success in graduate school (as outlined in Table 2). Because widely distributed information concerning the specific questions and situational assessments used would obviously threaten the validity of the interview and undermine the goal of this work, they are not included in the present paper, but professors interested in obtaining a copy of the question sheet can contact the authors (e-mail address: dube@genie.uottawa.ca).

A TYPICAL INTERVIEW

A typical interview is presented here with omission of certain specific details in order to protect the validity and reliability of the interview.

Prior to the interview, an academic transcript is obtained from the candidate; it is scored based solely on third- and fourth-year marks since these are, in our opinion, generally more representative of current performance in chemical engineering than first- and second-year marks.

An academic quality score is obtained in the following manner: 1 for an average below 75%; 2 for an average from 75 to 79%; 3 for an average from 80 to 84%; 4 for an average from 85 to 89%; and 5 for an average of 90% or greater (the scale chosen here could also be based on grade-point averages or letter grades). We suggest incorporating the use of reference letters only if they are submitted by reliable sources. It is, however, always advisable to check references.

The candidate’s writing skills can also be assessed via their letter requesting the interview. If the candidate comes from within the interviewing department, ask him/her to submit a formal written request for the interview. This letter can then be graded for grammar, structure, spelling, etc., and scored out of 5. (We consider it a plus if the student has enough foresight to have the letter proofread by someone.)

At the beginning, the interviewer should put the student at ease by doing most of the talking. This is an opportune time to tell the candidate about your own expectations and about your research. When the “sales pitch” is completed, it is time to begin the structured interview. The student should be informed that he/she is now going to be evaluated in a consistent and equitable manner by being asked the same questions as any other candidate. (In our experience, this explanation satisfies students who are very accepting of structured interviewing, most likely because they understand the importance of using a fair and empirically validated method of selection.) You may choose to allow the student to take notes.

The interview proceeds with the posing of questions and presentation of scenarios to which the candidate must respond. For instance, in order to assess oral communication skills, the candidate can be asked to tell the interviewer about his/her hobbies and interests. During this time, the interviewer should concentrate on the oral communication skills of the candidate rather than giving careful attention to the content of what is being said. The candidate can be given 1 point for each of the following criteria: eye contact, audibility, command of the language, grammar, and a logical progression of ideas.

The creative ability of the candidate can be evaluated by posing a technical problem that you are currently trying to solve. The candidate can be given 1 point for each of the following criteria: explanation satisfies students who are very accepting of structured interviewing, most likely because they understand the importance of using a fair and empirically validated method of selection.) You may choose to allow the student to take notes.

The candidate’s interpersonal skills can be assessed by proposing a scenario in which a conflict with a co-worker arises. Scores can be allotted based on how the candidate proposes to resolve the conflict.

Some skills cannot be assessed simply by an applicant’s verbal response to a simulated scenario. This is the case for the candidate’s laboratory skills and computer skills. For example the candidate could be invited to perform simple laboratory-skills tests and then be observed for errors such as improper measurements, inefficient use of equipment, poor calculations, inability to follow instructions, haste, cleanliness, etc.

Clearly, no single characteristic can be perfectly assessed using a single structured interview question. But together, the questions comprising the structured interview serve to give a more valid indication of the candidate’s future performance.

The total score should be calculated immediately after the student leaves. If so desired, the questions can be weighted differently, depending on their relative importance as per...
ceived by the interviewer.

A professor can refine a structured interview to more accurately reflect the required skill set. Skills or qualities can be added and extra questions or hands-on tests can be incorporated into the interview as needed. Conversely, certain skills or qualities can be eliminated. In other words, the interview is based on a situational assessment of the specific requirements for the job. Not all supervisors (or departments) are created equal. Some may want a very independent, ambitious, and creative student, while others may want what amounts to a technically skilled, obedient, and dependable laboratory technician.

One challenging situation involves the implementation of a structured interview in the case of international students. A long-distance phone interview, or video conferencing, or similar technologies may provide a partial solution. It may also be possible to have an on-site trusted colleague perform all or part of the interview.

The interview procedure discussed here can be somewhat lengthy, but when one expects to work with the candidate for a period that can span two to six or more years, it makes sense to spend a reasonable amount of time on the selection process. This is particularly important given the time and effort required to supervise graduate students and the significant contributions that talented students can make. Thus, it appears worthwhile to invest energy in developing strategies for selection that incorporate the latest available expertise. This structured interview is currently being implemented and data are being collected regarding its success in predicting performance.

As mentors, it is important to model fairness and integrity. Use of a structured interview can convey these values and demonstrate to students that their evaluation is based on competencies and not on irrelevant personal traits.

ACKNOWLEDGMENTS

Many thanks to Professor Willi Wiesner of McMaster University and Dr. David Lynn for their helpful discussions. Many colleagues were involved in the initial discussions regarding the qualities possessed by top graduate students, and for this they are gratefully acknowledged.

REFERENCES

TOWARD TECHNICAL UNDERSTANDING

Part 2. Elementary Levels

J.M. Haile
Clemson University • Clemson, SC 29634-0909

This is the second of three papers* that stalk the question of what we mean by an understanding of technical material. In the first paper of the series, we noted that to understand has multiple meanings; our goal in these papers is to clarify the distinctions among those meanings and to organize them into a useful hierarchy. We also summarized what is now known about the structure and function of the human brain, and we used that knowledge to draw certain implications about the nature of learning.

Any study involves many kinds of understandings and many ways to reach any of them. We propose that the ways of understanding technical material can be organized in a hierarchical fashion so that a progression through the hierarchy carries the student, in a systematic way, to a broader and deeper appreciation, perception, and comprehension of the material. The hierarchy consists of seven levels, shown in Figure 1.

In formal educational settings, much of a student’s effort seems to be devoted to solidifying understanding at the current level, while much of the instructor’s effort seems to be devoted to preparing students for the transition to the next level. Since the transitions carry the student to higher levels of understanding, the transitions between levels must be as important as the levels themselves.

A successful transition involves at least the two following characteristics. First, each transition must be motivated. In the early stages (levels 1 to 5), the transitions are motivated when we realize that mastery at the current level is not sufficient for our immediate needs. In the later stages (levels 5 to 7), the transitions are motivated when we realize that mastery at the current level enables us to move beyond our immediate needs. Second, each transition involves a reformulation of understanding at the current level. That is, understanding at the new level subsumes, but does not replace, understanding at previous levels. In each of the following sections, we first discuss a level and then provide the motivation and reformulation that constitute the transition to the next level.

LEVEL 1: MAKING CONVERSATION

Study begins when our attention is drawn to the objects, processes, and concepts that constitute a topic. At this most superficial level, understanding is just sufficient to enable students to participate in conversations about the topic. They at least know the names of some of the subject’s primitive objects and concepts, so they can pose questions. With more exposure, they may even be able to converse fluently about the material. Yet at Level 1, they still lack any skill in using the objects and concepts.

For conversation to succeed as communication, participants must properly use the names of objects and concepts. It is a seductive misconception, however, to believe that the correct use of a name implies a correct understanding of the named object. For primitive humans, a name was thought to be an intrinsic part of an object, and that calling the name of an object exerted control over it. Thus, one of Adam’s first acts in the Garden of Eden was to name the animals. Joseph Campbell has noted that in some ancient Indian cultures, pronouncing the Sanskrit name of a god was thought to call forth the god.\(^\text{[1]}\) A similar tradition operated in ancient Judaism, so that correct pronunciation of the name of God (YHVH) was first held secret, then later avoided. In fact, in Judaism and other ancient cultures, names were considered to be so powerful that the entire universe was thought to have been created, not out of nothing, but from a calling of names.\(^\text{[2]}\)

This ancient penchant for names was not intended to sig-
nal understanding, but rather to compensate for lack of understanding. In modern times, we may still use names to deal productively with things we don’t understand (an example is gravity). That is, sometimes we find it useful to substitute a name in place of the object named, even when the object itself is not understood.

In the classroom, however, manipulating names in place of objects can obscure rather than enlighten. Consider Feynman’s example of triboluminescence, which can be described as the emission of a photon that may occur when certain crystals are subjected to sudden high pressure.[3] Such a statement may be precise, but it really only trades one name for other names (photon, crystal, emission, pressure); to attach meaning to such a statement, a student must explicitly connect these names to physical objects. Left to their own devices, many students fail to make such connections. They can be helped by translating formal descriptions into more familiar terms, such as this: when a few grains of sugar are taken into a dark room and squeezed with a pair of pliers, we might see a small flash of light—that’s triboluminescence.[4] Names can help draw our attention to things, but knowing names is only a first step toward understanding.

**Transition:**

**Level 1 (Making Conversation)**

**Level 2 (Identifying Elements)**

**Motivation:** Verbal fluency with a portion of a domain is not the same as having clear ideas about the objects comprising the domain, or knowing which objects are most important, or knowing how the objects can be used.

**Reformulation:** Vague and ambiguous ideas are reduced to concise and accurate statements about the structure and function of objects and concepts.

**LEVEL 2: IDENTIFYING ELEMENTS**

When we identify the elements—the objects and concepts—that constitute a topic, we define the elements and try to give a sense of how the element behaves in typical situations. Let’s consider definitions first: a complete definition should encompass both structure and function. A structural definition should include two things: the identity of the class to which the object belongs and a list of those characteristics that distinguish it from other members of its class. A functional definition should also include two things: the typical or common use of the object, together with identification of situations where the object is not useful or in which it fails. The words used in these definitions must be words already known to the students; we are trying to build foundations in students’ minds by reorganizing and expanding what they already know, and we can only build from the materials available.

Structural and functional definitions should be provided for concrete things, abstract things, and processes. We tend to define concrete things in terms of function (a valve is a pipe fitting used to control flow) and to define abstractions in terms of structure (entropy is the thermodynamic state function obtained by applying an integrating factor to the inexact differential formed by the reversible heat). To the extent that this observation is true, it is one source of students’ discomfort with abstractions. To help us remember that both structure and function are important, here are five diagnostic questions that students and instructors can use to test understanding of elements:

1) What is it?
2) How is it related to or how does it differ from other members of its class?
3) For what is it used?
4) How can it fail?
5) How can we learn about it?

These diagnostics are illustrated in Table 1 for a concrete thing and for an abstraction. In addition to objects, these diagnostics can also be applied to processes; you might care to practice by applying them to flash distillation.

Note that questions (1) and (2) are ontological in that they address structure; questions (3) and (4) are causative in that they address function; and question (5) is epistemic.[6] For concrete things, a typical response to question (5) is to take the thing apart or to operate it. For mathematical abstractions, a typical response is to explore the object’s behavior by doing calculations with simple models. Note also that question (5) is intended to move the student from pure definitions toward meaning. That is, definitions do not necessarily constitute meaning, because meanings generally involve cross connections among objects, concepts, and levels of understanding. Consider,

When an ideal gas is heated in a closed rigid vessel, its internal energy always increases.

---

**Fall 1997**

---

**Figure 1.** The levels of understanding and the transitions between them.
The unfortunate—such as a politician or a royal person—might well know the definition of each word in this sentence without grasping the meaning of the sentence. To move toward meaning, students must participate in some of the activities suggested by the answers to question (5).

Transition:

**Level 2 (Identifying Elements)**

**to**

**Level 3 (Recognizing Patterns)**

**Motivation:** Knowing the identities and uses of individual objects is not the same as knowing how the objects are related or how they can be combined to increase their effectiveness.

**Reformulation:** Individual objects and concepts are organized into meaningful patterns.

**LEVEL 3: RECOGNIZING PATTERNS**

Structural and functional definitions can be given to most objects, concepts, and processes, but such definitions carry little meaning until the defined things are related to other objects, concepts, and processes. We use the word pattern to refer to those relations that impart meaning to sets of objects, concepts, and processes. For example, structural and functional descriptions of fugacity are given in Table 1; but meanings for fugacity can only be extracted from its relation to processes (such as diffusion) and to other properties (such as temperature and composition). Thus, a fugacity gradient measures a driving force for diffusion: a substance diffuses from a region of high fugacity to one of low fugacity. Moreover, when a fugacity is balanced across an interface, we have an absence of diffusional driving forces, producing diffusional equilibrium. Thus, the fugacity fits into a general pattern that uses driving forces to explain changes.

Other meanings can be attached to the fugacity by considering other relations. In fact, a general observation is that one object may participate in several different patterns and, moreover, that more than one pattern can often be contrived from the same set of objects and concepts. This is illustrated schematically in Figure 2. From the same objects, different patterns provide flexibility in that one pattern may prove more useful in one situation while another serves better in another situation. This flexibility leads to a problem-solving strategy; when a particular pattern of known information does not seem to be leading to a solution, try reformulating the information into a different pattern. When we say a concept is rich in meaning, we imply that it contributes to multiple patterns.

One of the great mathematical physicists of the 19th century, Henri Poincaré, had an understanding of classical dynamics that anticipated modern studies of nonlinear dynamics, unstable systems, and chaos. He was also deeply curious about the nature of creativity and the workings of the mind. In addressing the question as to why most people cannot understand mathematics, Poincaré wrote(7)

A mathematical demonstration is not a simple juxtaposition of syllogisms, it is syllogisms placed in a certain order, and the order in which these elements are placed is much more important than the elements themselves.

Such ordering of elements produces patterns, so we can

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Object</th>
<th>Fugacity</th>
</tr>
</thead>
</table>
| (1) What is it? | Valve whose body houses a chair-shaped seat located roughly mid-way between body walls. At the lower end of the stem is a disk that fits into a seat when the stem is lowered. | In a mixture containing component i at mole fraction \(x_i\), the fugacity \(f_i\) is the thermodynamic state function obtained from the following isothermal derivative of the chemical potential: 
\[
d\mu_i = RT \ln f_i 
\]
with low-pressure boundary condition 
\[
l_\lim_{P \to 0} = x_i P. 
\]
| (2) How is it related to or how does it differ from other members of its class? | Distinguished from others by globular shape of body. | Differs from chemical potential \(\mu_i\) and activity \(a_i\) in that absolute values can be obtained for fugacity \(f_i\), but only relative values can be obtained for \(\mu_i\) and \(a_i\). |
| (3) For what is it used? | For fine control of flow, as opposed to gate and ball valves, which only provide on/off control. | To express criteria for phase and reaction equilibria; thus fugacity provides starting points for solving phase and reaction equilibrium problems. |
| (4) How can it fail? | Worn seat and disk; leaks in packing; jammed stem; stripped threads on stem; solid matter blocking seat. | Not useful unless a model (such as a PVTx equation of state) is available that relates \(f_i\) to measurables, such as \(T\), \(P\), and \(x_i\). |
| (5) How can we learn about it? | Study design drawings; study cut-away model; take one apart; operate one in situ; operate one in a process simulator. | Explore its \(T\), \(P\), and \(x_i\) dependence by performing calculations using simple models. |
interpret this statement by saying that people fail to understand meanings to the extent that they fail to recognize and interpret patterns.

The pattern is the fundamental unit of understanding not just in mathematics, science, and engineering, but in any intellectual activity. For example, in music a single note or chord has essentially no meaning; musical meaning arises only when notes are organized into patterns. In the piano music of Bach, for example, many patterns can be identified as mathematical transformations of some relatively simple theme. Experienced musicians do not study music at the level of notes but at the level of phrases—patterns of notes. Similarly, masters at chess study their game not in the positions of individual pieces, but in the patterns produced by the relations among the positions. It is intimate familiarity with patterns that allows a master to play, and win, several games simultaneously.

Patterns are distinct from classifications. Classifying objects according to common characteristics helps us organize information, and it may help us identify relations and patterns, but a classification does not establish relations among objects. Note also that a meaningful pattern does not necessarily result when we simply organize information into a familiar structure. In the use of language, this observation motivates the distinction between syntax (proper structure) and semantics (meaning). For example, consider this German sentence from Wiener.

Der Geist will es, aber der Fleisch ist schwach.

A syntactically correct, word-for-word translation would be "The ghost want to, but the meat is rare." Although this translation preserves the syntax of the original, it fails to capture the meaning. In a syntactically correct structure, meaning is rarely embedded in individual elements; rather, it is usually gleaned from relations among the elements. A meaningful pattern is more than the sum of its parts.

Confusion as to the distinction between syntax and semantics seems pervasive and a cause for concern. We now have software that can check the spelling and grammar used in student themes, lab reports, and term papers; we have equation solvers by which students can readily implement all kinds of numerical methods; we have symbolic manipulators that students can use to take derivatives, evaluate integrals, and perform algebra; we have process simulators that students can use, not only to perform complex design calculations, but also to replace experience in laboratories. Over a period of just a few years, we have introduced an astonishing number of black boxes into our courses, with little concern about their impact on understanding gained or lost by students. The point here is that a syntactically correct manipulation of a black box does not necessarily evoke any semantically correct response from the student who operates the box.

In the hands of an expert, a black box can offer positive benefits—it can enable more work to be done in less time. Experts attach meaningful relations between input and output, and they are sensitive to any deviation from an expected outcome. If an outcome is unexpected, they have other independent means for checking. But a positively beneficial tool in the hands of an expert can be positively dangerous in the hands of a novice. Novices cannot make logical and meaningful relations that connect output to input, they have ill-formed expectations as to what the output should be, they are not aware of how a black box can be wrong, and they have few if any independent mechanisms for checking the output.

Given our present understanding of how minds work, it is difficult to see how a black box, which is intended to hide the relations between output and input (i.e., hide patterns), can be used to establish meaningful relations in the brains of students. It may be, however, that some use of black boxes can reinforce or strengthen patterns that have been established through other learning activities. Thus, a black box should be introduced only after students have developed understanding about those relations hidden by the box.

Since the cerebral cortex learns by modifying existing structures, presenting new patterns should always proceed inductively, starting from particulars. For example, say the goal is to develop the pattern we call the stuff equation:

\[
\begin{array}{cccc}
\text{Rate of} & \text{Rate of} & \text{Rate of} & \text{Rate of} \\
\text{STUFF into} & \text{STUFF out} & \text{generation} & \text{consumption} \\
\text{system by} & \text{of STUFF} & \text{of STUFF} & \text{of STUFF} \\
\text{interactions} & \text{by interactions} & \text{in system} & \text{in system} \\
\end{array}
\]

We should start with a particular application, preferably extracted from the student's experience—balancing a check
Patterns are effective devices because minds seek patterns. Since minds try to find patterns in any case, we might as well try to develop patterns that are known to be effective and useful. Conversely, we should help students avoid patterns that are misleading or unproductive. That is, we should devote some effort to showing students ways not to think.

Patterns are also effective because they provide a means for attaining efficiency in education. With the quantity of technical information doubling every five years, how can we ever teach it all? The answer is not merely that we can't, but more importantly, that we shouldn't. Repeatedly presenting new applications without establishing any overriding pattern wastes resources because it provides no lasting benefit to students. The purpose of a university education is not to simply teach facts or to train operators of black boxes; rather, it is to develop a small core of important patterns in the brains of students. Important patterns are those that will help students grow by adding new information to their existing core. Likewise, new information is important to the extent that it connects to old information and established patterns; without such connections, new information is isolated and essentially meaningless. By extension, we should not teach any topic that lacks patterns that could serve as a basis for future growth of students.

**Transition:**

**Level 3 (Recognizing patterns) to Level 4 (Solving Problems)**

**Motivation:** Recognizing a pattern is not the same as knowing how the pattern can be used or recognizing situations in which it can be used.

**Reformulation:** The pattern is connected to problem situations—contexts in which the pattern takes on particular meanings.

**LEVEL 4: SOLVING PROBLEMS**

At previous levels, our attention is focused on identifying, defining, and attaching meaning to objects, concepts, and patterns. Now we begin to use those objects, concepts, and patterns to answer questions; the formulation of answers is called problem solving. To solve problems, not only must we be aware that certain patterns exist, but we must also recognize when they are useful. That is, patterns themselves are useless until they are related to still other patterns, objects, and concepts. These other related things constitute a context in which a pattern acquires a particular meaning. The act of recognition amounts to a projection of relevant information onto an appropriate pattern in the problem context. In the language of group theory, such a projection is homomorphic in that only relevant information is projected; irrelevancies are suppressed. This is illustrated schematically in Figure 3. These projections are usually homomorphic because reality nearly always provides more information than we need. Recognition of the appropriate projection is a vital step in solving a problem.

To illustrate a homomorphic projection, say we are faced with a heat exchanger that is no longer operating to specifications. One diagnostic would be to check the energy balance. Thus, we determine the temperatures, pressures, compositions, flow rates, and phases of all streams and project them onto the pattern of the stuff equation; under this projection the stuff equation becomes an energy balance. This projection is homomorphic in that we need only information about streams into and out of the exchanger; information about the interior of the exchanger, such as heat transfer areas and heat transfer coefficients, is suppressed. The result of the energy-balance calculation may or may not help us solve the problem; if it does not, then we seek other patterns. The lessons here are that the problem context suggests patterns that may be useful and the context imparts meaning to the results obtained from the patterns. Thus, say we find that the energy balance is satisfied with ±3%; is this satisfactory or not? The answer depends on context. In some situations ±3% would be perfectly satisfactory, but in others it would be absolutely devastating. Students often have difficulty reconciling the meaning of a computed number to the context of the calculation.

The projection from the observable world onto a pattern in the problem context is a first step in developing a solution procedure. The development of a complete procedure is an important aspect of achieving understanding at Level 4; we do not address the detailed aspects of that development here, however, because a considerable body of literature already exists. The modern literature on solving problems begins with Polya, and a continuing survey is available from Woods. We do, however, emphasize three general points about solving problems.
First, we have two general strategies for solving problems: an offensive strategy, in which we try to move toward a stated goal, and a defensive one, in which we try to avoid undesirable penalties. In most situations, we use an offensive strategy, but if we can’t find a successful offensive strategy, then we should consider a defensive one. The lesson here is to maintain flexibility; in some situations, penalty avoidance is sufficient to be successful. For example, an offensive strategy guides most investments in the stock market (the goal is to increase capital), but in some markets the winning strategy is a defensive one (to avoid losing capital).

Second, one mistake that commonly prevents our solving a problem is a failure to verify default assumptions. Default assumptions are those many aspects of experience that we take to be generally true. Such assumptions free us from having to repeatedly make the same judgment about a familiar situation. Without default assumptions, we could rarely find time to accomplish anything new. But sometimes we cannot solve a problem because a default assumption no longer applies. Polya lists several in a mathematical context, such as

1) If we have $N$ equations in $N$ unknowns, then we can solve for the unknowns.

Here are some others:

2) If a simple algorithm provides a result, a complex algorithm will provide a more reliable result.
3) If a statement is true, then so too is its converse.
4) If any data fail to fit the expected pattern, we can ignore those data.
5) If two effects are similar, then their causes are similar. This assumption takes several forms, including: Large effects have large causes.
6) If the problem has boundaries, then its solution has the same boundaries.

Confining the search for a solution to the boundaries of the problem is a common source of difficulties; in some situations, simply extending the boundaries converts an intractable problem into a trivial one.

Third, in problem solving, memory plays multiple, conflicting roles. On one hand we need long-term memories to recall patterns that might be helpful in the current problem context. (These might be evoked from Polya’s heuristics.) Have you ever solved this problem before? Have you ever solved a similar problem?) On the other hand, we need short-term memories to identify our current position in the solution procedure, to recall how results from previous steps affect the current step, and to recall how results at the current step are to be used in subsequent steps. The simultaneous use of these memories seems to interfere with creation of new memories; that is, in any challenging problem, so many neural networks are activated that few are available for forming new memories. When we solve a new problem for the first time, our attention is so preoccupied with finding the solution that we rarely learn how to solve it. This observation motivates the transition to Level 5.

**SUMMARY**

In this paper we have suggested that the multiple meanings for technical understanding can be organized into a hierarchy, and we have described understanding at the elementary levels. In our discussion of those levels, an important point has emerged: the fundamental unit of understanding is the pattern. Patterns impart meaning by providing structures that establish relations among chunks of information, so our understanding of a topic remains rudimentary until we can see patterns. Further, we advance to higher levels of understanding only to the extent that we can recognize, interpret, and apply patterns. The importance of this point can probably not be overemphasized. We conjecture that one of the most effective improvements we can make in education is to organize material so that students learn patterns, not sequences of individual facts.

As students progress through the first levels of understanding, they move from an initial encounter with a topic to some facility with solving problems. So, when they are able to solve problems at Level 4, they have made significant progress. Nevertheless, achieving skill at solving problems marks a rather elementary level of understanding; solving a problem is not the same as knowing how to solve it. This realization begins the transition from Level 4 to Level 5. This transition is often difficult to make and therefore it is the one we use to distinguish elementary understanding from more advanced levels. Those advanced levels will be described in the third paper in this series.

**REFERENCES**

2. Genesis, Ch. 1; *Gospel of John*, Ch. 1, V. 1
4. It is now known that triboluminescence is an artifact caused by impurities in the crystals.
11. Woods, D.R., *PS News*, a newsletter on problem solving, published bimonthly at the Department of Chemical Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7
Once again the fall semester has snuck up on me while I was looking the other way. Among the things I was definitely going to do this summer but didn’t is the fall-issue Random Thoughts. I decided to rerun the first column in the series (Fall, 1988) instead, confident that most of you are too young to remember it (and even more confident that you didn’t do what you were going to do this summer either, so you should have no trouble relating).

He knocks on my office door, scans the room to make sure no one else is with me, and nervously approaches my desk. I ignore the symptoms of crisis and greet him jauntily.

“Hi, Don—what’s up?”

“It’s the test tomorrow, Dr. Felder. Um ... could you tell me how many problems are on it?”

“I don’t see how it could help you to know, but three.”

“Oh, Uh ... will it be open book?”

“Yes—like every other test you’ve taken from me during the last three years.”

“Oh ... well, are we responsible for the plug flow reactor energy balance?”

“No, it happened before you were born. Look, Don, we can go on with this game later, but first how about sitting down and telling me what’s going on. You look petrified.”

“To tell you the truth, sir, I just don’t get what we’ve been doing since the last test and I’m afraid I’m going to fail this one.”

“I see. Don, what’s your GPA?”

“About 3.6, I guess, but this term will probably knock it down to ... “

“What’s your average on the first two kinetics tests?”

“92.”

“And you really believe you’re going to fail the test tomorrow?”

“Uh ... .”

Unfortunately, on some level he really does believe it. Logically he knows he is one of the top students in the department and if he gets a 60 on the test the class average will probably be in the 30’s, but he is not operating on logic right now. What is he doing?

The pop psychology literature calls it the impostor phenomenon. The subliminal tape that plays endlessly in Don’s head goes like this:

I don’t belong here ... I’m clever and hard-working enough to have faked them out all these years and they all think I’m great, but I know better ... and one of these days they’re going to catch on ... they’ll ask the right question and find out that I really don’t understand ... and then ... and then ...

The tape recycles at this point, because the consequences of them (teachers, classmates, friends, parents, ...) figuring out that you are a fraud are too awful to contemplate.

I have no data on how common this phenomenon is among engineering students, but when I speak about it in classes

Richard M. Felder is Hoechst Celanese Professor of Chemical Engineering at North Carolina State University. He received his BChE from City College of CUNY and his PhD from Princeton. He has presented courses on chemical engineering principles, reactor design, process optimization, and effective teaching to various American and foreign industries and institutions. He is coauthor of the text Elementary Principles of Chemical Processes (Wiley, 1986).
and seminars and get to "... and they all think I'm great, but I know better ...," the audience resonates like a plucked guitar string—students laugh nervously, nod their heads, turn to check out their neighbors' reactions. My guess is that most of them believe deep down that those around them may belong there but they themselves do not.

They are generally wrong. Most of them do belong—they will pass the courses and go on to become competent and sometimes outstanding engineers. But the agony they experience before tests and whenever they are publicly questioned takes a severe toll along the way. Sometimes the toll is too high: even though they have the ability and interest to succeed in engineering, they cannot stand the pressure and either change majors or drop out of school.

It seems obvious that someone who has accomplished something must have had the ability to do so (more concisely, you cannot do what you cannot do). If students have passed courses in chemistry, physics, calculus, and stoichiometry without cheating, they clearly had the talent to pass them. So where did they get the idea that their high achievements so far (and getting through the freshman engineering curriculum is indeed a high achievement) are somehow fraudulent? Asking this gets us into psychological waters that I have neither the space nor the credentials to navigate; suffice it to say that if you are human you are subject to self-doubts, and chemical engineering students are human.

What can we do for these self-labeled impostors?

Mention the impostor phenomenon in classes and individual conferences and encourage the students to talk to one another about it.

There is security in numbers; students will be relieved to learn that those around them—including that hotshot in the first row with the straight-A average—have the same self-doubts.

Remind students that their abilities—real or otherwise—have sustained them for years and are not likely to desert them in the next twenty-four hours.

They won't believe it just because you said so, of course—those self-doubts took years to build up and will not go away that easily. But the message may get through if it is given repeatedly. The reassurance must be gentle and positive, however; it can be helpful to remind students that they have gone through the same ritual of fear before and will probably do as well now as they did then, but suggesting that it is idiotic for a straight-A student to worry about a test will probably do more harm than good.

Point out to students that while grades may be important, the grade they get on a particular test, or even in a particular course, is not that crucial to their future welfare and happiness.

They will be even less inclined to believe this one, but you can make a case for it. One bad quiz grade rarely changes the course grade, and even if the worst happens, a shift of one letter grade changes the final overall GPA by about 0.02. No doors are closed to a student with a 2.84 GPA that would be open if the GPA were 2.86. (You may not think too much of this argument, but I have seen it carry weight with a number of panicky students.)

Make students aware that they can switch majors without losing face.

It is no secret that many students enter our field for questionable reasons—high starting salaries, their fathers wanted them to be engineers, their friends all went into engineering, and so on. If they can be persuaded that they do not have to be chemical engineers (again, periodic repetition of the message is usually necessary), the consequent lowering of pressure can go a long way toward raising their internal comfort level, whether they stay in chemical engineering or go somewhere else.

Caution, however. Students in the grip of panic about their own competence or self-worth should be deterred from making serious decisions (whether about switching curricula or anything else) until they have had a chance to collect themselves with the assistance of a trained counselor.

One final word. When I refer at seminars to feeling like an impostor among one’s peers, besides the resonant responses I get from students I usually pick up some pretty strong vibrations from the row where the faculty is sitting. That’s another column.

REFERENCES

ON THE NATURE AND CONDUCT
OF TECHNICAL RESEARCH

JOHN P. O'CONNELL
University of Virginia • Charlottesville, VA 22903 USA

In 1589, a young man carrying a number of different spheres trudged to the top of the Leaning Tower of Pisa and proceeded to make an impact on history. After centuries of speculation about whether solid bodies of different sizes and densities would fall at the same or different rates, Galileo Galilei’s famous demonstration showed that mass and density make no perceptible difference in the rate of fall. His apparently courageous (or perhaps arrogant?) act of actually conducting the experiment and the ultimate impact of his results have been a source of inspiration for generations of scientists, encouraging them to take the “path less traveled” in making their own discoveries of significance.

According to Gerald Holton, Galileo was like most of the “scientists” of his era—quite different from today’s scientist. He performed most of his experiments privately and did not write about them (some historians challenge whether he did any experiments). But, back then as well as now, science was a search for cosmic truths based on thematic presuppositions—that is, beliefs and instincts pushed things forward. Thus, true to the science of his time, Galileo would have been convinced of his view about equal rates, and if the experiment had turned out different from what he expected, he might have been tempted to deal with the crisis in an unacceptable way, as Sidney Harris illustrates in Figure 1.

It is this story—and the cartoon’s “rest of the story”—that comprise the dual themes of this paper. The notions of what technical research is and how it is carried out are examined, especially in light of today’s technology and objectives. But, even when we know what to do, we have to deal with various pressures—the pressure to produce, the limitations on our resources, the calls for elimination of everything that is not immediately and directly applicable, and the demands to “fix up” an ailing research establishment. These pressures may lead us away from the true quest of research and into unprofessional conduct. My goal here is to help research advisors and their coworkers to more fully appreciate technical research and to improve their performance. The references listed at the end of this paper are only a few of the many available, and there is a wealth of material in them,
The rewards of a life spent in research are both personal and communal, although the latter is often not fully appreciated. Research findings contribute to the total body of knowledge, giving the research scientist a valid sense of community and commonality.

especially concrete suggestions. Finally, I will demonstrate one way to use the case studies in the National Academy’s booklet[2] to give graduate students some experience with research dilemmas and allow them to practice both group work and oral communication.

First, the assumption is that researchers want to do the best they can. If they fall short, it is probably not because they want to get away with the minimum amount of work possible or, worse, that they just don’t care or, worst of all, that they cheat. Human frailty, limited experience, and value conflicts are usually the cause of confused behavior.

“A Corollary to Murphy’s Law”

<table>
<thead>
<tr>
<th>Do not ascribe to</th>
<th>malice what can be ascribed to</th>
</tr>
</thead>
<tbody>
<tr>
<td>incompe nce</td>
<td>ignorance</td>
</tr>
<tr>
<td>insensitivity</td>
<td></td>
</tr>
</tbody>
</table>

While sometimes bad things are intended, mostly they’re not!

Also, although the discussion in my resource materials is often couched in terms of “science” because many of the leaders and speakers are scientists, the truths discussed here also work for engineering and engineering science research. Applied research has the same ultimate effect as does basic research: “to make claims about the world that are subject to empirical tests.”

WHAT IS RESEARCH?

The most relevant definition of research in the 1971 Oxford English Dictionary is:

“Research 3. A search or investigation directed to the discovery of some fact by careful consideration or study of a subject; a course of critical or scientific inquiry.”

Early usage includes:

“The matter lies deep in Nature and requires much research...[to] unfold it.”

W. Holder, 1694.

“Our most profound researches are frequently nothing better than guessing at the causes of the phenomena.”

J. Robertson, 1799.

This definition is pretty dry, perhaps circular, and even depressing—as are most definitions. Interestingly, the idea of research has been around for centuries, yet it is young in human history. Also, scientific truth is not fixed and universal. Not only does the “truth” evolve, but even the methods of scientists to decide about truth change and continue to develop.[1] But there seems to be a force that attracts people of all persuasions, all over the world, to observe and develop new, more accurate, more complete, and more useful descriptions of the physical, biological, and social world.

WHY DO PEOPLE DO RESEARCH?

What is it that drives people to conduct research? It is, after all, a process that can consume lives. The geneticist, Barbara McClintock, observed,[2] “I was just interested in what I was doing. I could hardly wait to get up in the morning and get at it. One of my friends, a geneticist, said I was a child, because only children can’t wait to get up in the morning to get at what they want to do.” What a wonderful way to live!

Success at research can engender the joy of triumph. A book by Sinderman[3] describes both the techniques and the rewards of a life spent in scientific research. Although such views can encourage a person to consider such a commitment, real experience is needed to decide if the effort is personally worthwhile.

The rewards of a life spent in research are both personal and communal, although the latter is often not fully appreciated. Research findings contribute to the total body of knowledge, giving the research scientist a valid sense of community and commonality. The positive aspects most researchers cite are

1. They like it; it is exciting and fun!
2. Success can yield personal and communal triumph.
3. They associate with people who care about similar concerns.
4. Challenging assumptions and seeking new things are stimulating.
5. Confidence comes from relative freedom and responsibility.
6. They belong to a community based on trust and honest recognition.
7. The results can make positive impacts on society.

Of course, there is also a down side:

1. Many failures in measurements or hypotheses are found (Murphy’s Original Law, “If anything can go wrong, it will!”).
2. Disagreements over results, interpretation, or credit sometimes arise.
3. Success is sometimes minimized because of different value structures (“It must have a practical use!”).

The most negative view of research that I have found was expressed by Sir Francis Bacon:[4] what research encounters in the “subtlety of Nature, the secret recesses of truth, the obscurity of things, the difficulty of experiment, the implication of causes, and the infirmity of man’s discerning power,

Fall 1997
Think of every way possible to shoot down your own idea before you can begin to accept it.” It sort of works just isn’t good enough! One should ask, “Would I stake my job or career on this result?”

“Science has progressed through a uniquely productive marriage of human creativity and hard-nosed skepticism, of openness to new contributions and persistent questioning of those contributions and of the existing consensus.” And, as mentioned before, this process of validation also evolves as our knowledge and techniques advance.

WHAT KINDS OF CHALLENGES ARE ENCOUNTERED IN RESEARCH?

There are many problems involved in the performance of research. After all, if it could be done easily for fun and profit, everyone would plunge right in. Among the many issues that could be discussed, I will address only a few.

Experiments and Data Treatment

“To learn the secrets of Nature, we must first observe.”

Roger Bacon

“Developing theories without data is like making bricks without clay.”

Sherlock Holmes

“But ask... of the earth, ...and [it] shall teach you ...”

Job 12:7-8

After realizing the importance of conducting experiments, we need to use the results in the most effective ways. Some
things to avoid are:

1. Uncertain values or errors and noise due to unrecognized limits of technique or equipment.
2. Prevention of independent verification because of incomplete description of measurement conditions and/or analysis.
3. Distortion of reality by rejection/retention of inappropriate data points.
4. Prejudicial conclusions about the quality of a model from using incomplete or biased data.

We know that data can be fallible; this means that an organized and searching skepticism is necessary. The key question is how to work so that truth is maximized?

Consider three cases involving great scientists:

1) Lord Rayleigh discovered the element argon by noticing that the density of nitrogen gas prepared by absorption of oxygen from air differed from that of gas prepared by chemical formation. Considering the cause of the discrepancy led to the conclusion that there was more than just oxygen and nitrogen in air (which, in turn, had originated with the observation that these were the dominant and reacting components of air).

2) Physicist J. Donald Fermi says that in 1613 Galileo recorded the data needed to discover the planet Neptune. However, by either oversight or by rejecting his own drawing, it took 234 more years for Neptune to be "found."

3) Fermi also says that Michelson decided in advance that electrons had to come in integer values on his oil drops. As a result, he threw out a bunch of data that yielded 1/3 values and thus lost the opportunity to discover quarks at the same time!

Examining and validating all the data can result in more than meets the eye.

The treatment of measured data is handled thoroughly and well in the book by Wilson. I learned of a favorite case of MIT's pioneering chemical engineering professor Warren K. Lewis that might also be illustrative—the "Three-Point Dilemma" (see Figure 2). At first glance, it seems impossible to make sense of these data. But a correlation could be valid with information from a rigorous theory (such as the value at $x = 0$) and experimental uncertainties (see Figure 3). While the data may seem very rough, that's not the point: informed analysis gives maximum knowledge.

**Simulation**

Recent advances in computers allow computation, imaging, and synthesis of phenomena in incredible ways. Using it as a tool in our research repertoire, the computer pushes us amazingly far into quantitative descriptions of Nature, allows examination of multitudes of models, and creates images at all scales of distance and time that are unavailable experimentally. Simulation has become the most ubiquitous and hottest methodology ever known.

**Figure 2. The Three-Point Dilemma: How to Draw the Correlation?**

Validating simulation requires the same care as experiment. In addition to the need for awareness about sensitivity, undetected assumptions, and insufficient sampling, there must also be detection of computer-code errors and adherence to reporting only believable significant figures. Multiple checks of limits and consistency are required.

I have heard more than once from Stanford Chemistry Professor Hans Christian Andersen, "Simulation is very seductive. But, like most things seductive, it is not necessarily wholesome." We probably have at least our share of fools and scoundrels in simulations since such care may not always be taken."

**Exploration**

Linus Pauling has quoted the physicist John Van Vleck as saying, "I have never made a contribution... that I didn't..."
get by fiddling with the equations.” Pauling then added his own aside, “I've never made a contribution that I didn't get by just having a new idea. Then I would fiddle with the equations to help support the idea.” (Here, “fiddling” does not mean faking or fantasizing—it means assessing the important and unimportant contributions and doing exploratory calculations. In that way, inadequacies in sign, trend, form and magnitude, including omissions, can be found, and one can connect proposed adjustments to physical and chemical insights.) Note that in both styles there was equation fiddling. Such fiddling was probably the dominant mode of quantitative exploration before extensive computations were possible. In this modern age of ever-increasing computer power and ease, we must remember that people should do the thinking and machines should do the work.

**Judgments, suppositions, and beliefs**

If Galileo had really encountered the spheres falling as depicted in the cartoon at the beginning of this article, he could respond as pictured only if there were evidence to the contrary and he knew why the Pisa experiment was flawed. But that would not be “altering the data.” Now we are better at developing our ideas while maintaining awareness of hazards in the process (see Table 2).

### WHAT ARE SOME OF THE ETHICAL ISSUES OF RESEARCH?

In addition to mastering the various techniques for gathering information, researchers must also recognize many ethical aspects. The US scientific enterprise has recently been questioned and threatened because of human issues. Today, the cartoon reaction could result in disbarment.

We must examine how the values of science are understood and practiced, especially in “conflicts of values” situations. This is the central focus of an article in *Science* and is a major portion of the booklet *On Being a Scientist.* Research programs in chemical engineering do not usually encounter such issues directly, but we abdicate our responsibilities as technical professionals and informed citizens if we do not consider what is involved in the ethical issues of technical research. Note that this introduces the one thing that research is supposed to avoid—irrationalities. They appear because research is a human process.

Margaret Somerville, director of McGill University's Center for Medicine, Ethics, and Law, put it succinctly, “[A sense of responsibility] is [the trait] I would put at the top. A scientist can be brilliant, imaginative, clever with his hands, profound, broad, narrow—but he is not much as a scientist unless he is responsible.”

The booklet *On Being a Scientist* lists some troublesome aspects arising from value conflicts in technical research:

- **Personal Interest:** financial involvement, confidential knowledge, etc.
- **Publications and Openness:** false claims of discovery, commercial proprietary secrets, multiple publication of the same work, many short papers
- **Allocation of Credit:** lack of proper recognition, citations, number of authors, and accountability
- **Errors and Negligence:** lax standards and quality, sloppiness, and lack of trustability
- **Misconduct and Deception:** fabricating data, falsifying results, plagiarism, cover-ups, reprisals against whistleblowers, malicious allegations, violation of due process in handling complaints

### Action in cases of unethical conduct

First, we must not be tolerant of—much less support—substandard conduct, especially when it comes to unethical behavior. If we know a wrong has been done, we are obligated to act. Inaction can cause problems ranging from mere obstruction to real damage to one's own research, particularly to the credibility necessary to have one's results trusted. Furthermore, if breach of trust is broadly found, the whole research community could fall under a cloud that maligns everyone, generates counterproductive regulations, and fosters widespread public doubt.

To take action in such cases requires courage and careful preparation. The essential first step is to have already estab-

---

**TABLE 2**

**Issues in Judgment and Self-Knowledge**

1. In selecting the best hypothesis to proceed with, look for:
   - A. Internal consistency
   - B. Accurate correlation and *prediction* of measurements
   - C. Unification of apparently disparate observations

2. Using personal intuition—the good and the bad
   - A. Will one's instincts and experience always lead to advances?
   - B. Is one always motivated by desire for truth, beauty, and quality?
   - C. What is really assumed in one's work? Is it a help or hindrance?
lished a reputation of honor and standards. Then the process must be carefully executed. The National Academy's report\[2\] recommends:

1. Long before the need arises, establish your own credibility.
2. Discuss the case with a trusted friend or advisor.
3. Find out your institutional procedures by
   • Calling your academic Office for Research (Vice Provost?)
   • Reading the general publications listed in On Being a Scientist\[2\]
4. Carefully choose the proper time to “put it in writing”—this is a major step.
5. Seek confidentiality, but don’t expect it. If you see a situation coming, plan ahead.

AN ACTIVITY FOR GRADUATE STUDENTS

On Being a Scientist\[2\] provides some excellent material for engaging students in the issues explored here. The booklet can be studied individually, in groups, or in a class. There are nine short case studies given as sidebars in the main body of the text, along with an appendix discussing them. The case titles are:

- Publication Practices
- Plagiarism
- Credit Where Credit Is Due
- Sharing of Research Materials
- Fabrication in a Grant Application
- A Conflict of Interest
- Industrial Sponsorship of Academic Research
- A Career in the Balance
- The Selection of Data

Each case study has a brief background of the situation with “real people” expressing opposite sides of the issues, followed by one to three questions that attempt to bring out the reader's view. The appendix provides some guidance, but does not establish the answer.

I made use of the material in the context of the Departmental Graduate Seminar. First, I gave a talk that was essentially the same as the text of this paper. After questions and a discussion, I requested the departure of all those who were not chemical engineering graduate students or who did not wish to participate in a deeper experience of the issues. I then asked the remaining students to break into groups of three, and I gave each group a copy of one of the cases. They were told that in three weeks, they would all be required to present the Graduate Seminar under strict rules. Each group would be given five minutes and four overheads to present their case, which should include a description of the situation, the issues, and their own resolution of the case. I also asked faculty members to volunteer as an advisor for each case. The students were expected to meet with the faculty member for discussion, and most of them did. Prior to this exercise we had issued guidelines for oral communications (based on the AIChE Speaker's Manual) and the students seemed to use this information to their advantage during their preparations. To promote community feelings about the effort and to provide a benchmark, I also gave out “Speaker Evaluation” forms for the students to judge the quality of my presentation. The compliments and criticisms were consistent with my assessment of my talk.

The day of student presentations was an excellent occasion. The seminar attendance was the largest in months, and the presentations ranged from quite good to superb. Finally, a survey of the students was taken about the difficulty of understanding and resolving the cases—some proved harder than others, but the students found all of them interesting. The faculty said that some groups really "got into" their cases, but no one was heard to say that the time and effort were wasted.

CONCLUSIONS

This paper has tried to introduce "eager, thoughtful, and reverent" workers to understanding and materials about technical research—what it is, why people do it, how it's done, some of the difficulties, and what to do about unprofessional conduct. Hopefully, some responsive chords have been struck. Research is challenging; since we are involved with it, all of its aspects should be of utmost importance to us.

ACKNOWLEDGMENTS

The author is grateful for the encouragement of his colleagues, especially younger ones, to complete this work for publication.

BIBLIOGRAPHY

The focus of the Yale University graduate course described in this paper is on aspects of combustion not usually part of the education of applied scientists or engineers (especially mechanical and aerospace engineers). Indeed, most available books in the field describe combustion almost exclusively in terms of power production and/or propulsion. These are, undeniably, areas in which combustion is usually an attractive option. But as emphasized here, combustion is also an extremely effective (and frequently the most economical) way to synthesize and/or upgrade needed materials.

Consider, for example, titania (white) pigment, briefly discussed later in this article. Each year, megatons are sold throughout the world at prices that exceed $1/kg. Most titania pigment is made by a chemical synthesis process involving combustion to generate high temperature oxygen and water vapor that react with injected titanium tetrachloride vapor to produce the desired pigment particles. More generally, it will be seen that not only are there many proven, highly developed combustion processes for synthesizing commodity chemicals world wide, there are also new processes, (some discovered only in the last ten years) that exploit combustion. Examples are the production of diamond films (Section 2.3) or fullerene molecules (C_{60}, polymer of carbon) (Section 2.4).

Buckminsterfullerene, C_{60}, is a completely novel (discovered in 1985) and rather expensive ($10,000/kg in 1996) “polymorph” of carbon that can be produced using benzene/oxygen flames. It happens to be a form of carbon presently “in search of applications.” Not surprisingly, alternate synthesis and separation methods are very active areas of research.

These relatively recent discoveries are now being exploited and commercialized. Thus, an important point to make at the outset is that there are not only mature technologies (constantly in need of improvement to retain their competitive edge) that exploit combustion to synthesize commodity chemicals, but combustion is also an option for synthesizing valuable new materials (films, fibers, particles, or molecules) that will motivate synthesis-oriented combustion research and development in the future.

In the graduate course described here, we have selected and discussed several instructive examples of both mature and recent materials synthesis technologies that exploit combustion. In each case, valuable glimpses were provided of these relevant issues: What are the current technological and competitive challenges? What kinds of fuels, oxidizers, and additives are involved? What are the reagent contacting patterns? How can such equipment be sized? What operating conditions (pressure, temperature, composition, etc.) will be optimal?

Additionally, materials can be upgraded using combustion techniques, i.e., there are many methods for cutting, resurfacing, or otherwise changing the nature of materials using combustion technology (Section 4). These examples, again, lead to the conclusion that if you and your students or colleagues find yourselves thinking of combustion only in terms of power generation and/or propulsion, you will inevitably
miss important opportunities. Indeed, much good research and development will be needed on these nontraditional (chemical engineering-) facets of combustion.

Another important purpose of this graduate course is to give engineering students from different disciplines an idea of how rather simple (preliminary) calculations can be made to estimate approximately how large these reactors must be in order to produce, say, a metric ton of product every hour using, in some cases, conventional types of combustion. For this purpose, frequent reference was made to the summary of attainable volumetric chemical energy release rates shown in Figure 1. Instructional student exercises were developed for each of these topics. Students were asked to put in real numbers and make the associated preliminary design calculations as a necessary first step to the more detailed follow-on calculations (often using proprietary codes). Each student also researched and prepared a written term paper on a particular combustion synthesis and materials processing (CS/MP) topic of interest to him or her (see Table 1).

Several introductory lectures were devoted to combustion fundamentals, including the chemical engineering core subjects of chemical thermodynamics and homogeneous/heterogeneous chemical kinetics. But CS/MP examples were used to teach the principles of chemical thermodynamics and chemical kinetics, flame stability (parametric sensitivity), etc. Thus, we considered the thermodynamics of diamond production (Section 2.3), and similarly, for chemical kinetics, we deliber-ately selected inorganic systems (e.g., the kinetics of Na(g) + TiCl_4(g) (Section 2.1), and not the usual hydrocarbon chemistry.

In its original form, this course was comprised of a two-part lecture each week for one semester (see Table 1). As done in this summary, the examples were divided into the production of valuable vapors (e.g., HCl, SO_2, P_2O_5, O_2, N_2, etc.), fine particles (carbon black, fumed silica, titania pigment, doped glass microdroplets for optical waveguides, etc.), and monolithic solids, all discussed later in this article. We went on to some interesting combustion applications in the area of materials processing (coating, cladding, smoothing, cutting, slurry drying, etc.) and concluded with remarks about the future importance of this less visible but commercially important branch of combustion engineering.

SECTION 1
Combustion Synthesis of Vapors

1.1 HCl Synthesis via H_2(g) + Cl_2(g)

An early "combustion-like" example I encountered for synthesizing vapors is really a class of co-flowing non-premixed gas burners. The reactor shown in Figure 2 can be purchased off-the-shelf for combining hydrogen and chlorine to produce (and then to condense) pure hydrochloric acid. In this way, one could specify

![Figure 2. "Off-the-shelf" HCl synthesis reactor via H_2(g) + Cl_2(g) "diffusion flame."](image)

<table>
<thead>
<tr>
<th>Lecture #</th>
<th>Topic(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction to CS/MP: Course Scope, Fundamental/Technical Importance</td>
</tr>
<tr>
<td>2</td>
<td>Review of Relevant Thermochemistry and Chemical Kinetics</td>
</tr>
<tr>
<td>4</td>
<td>Combustion-Synthesis of Valuable Vapors: Acetylene, HCl, SO_2, P_2O_5, etc.</td>
</tr>
<tr>
<td>5</td>
<td>Combustion-Synthesis of Ultrafine Particles: carbon black, fumed SiO_2, TiO_2</td>
</tr>
<tr>
<td>6</td>
<td>Combustion-Synthesis of Ultrafine Particles (continued): doped SiO_2, V_2O_5, TiO_2 catalyst</td>
</tr>
<tr>
<td>7</td>
<td>Chemical Stability of Powders: &quot;Pyrophoricity&quot; and Ceramic Monolith Synthesis via Powder Chemical Reactions (&quot;SHS&quot;)</td>
</tr>
<tr>
<td>8</td>
<td>Combustion Synthesis of Coatings; e.g., diamond films</td>
</tr>
<tr>
<td>10</td>
<td>Combustion Surface Treatment: Flame &quot;Polishing,&quot; Spheroidization, Sintering, and Cladding</td>
</tr>
<tr>
<td>11</td>
<td>Oxy-Fuel Combustion for Cutting, 'Gas' Welding, and Brazing</td>
</tr>
<tr>
<td>13</td>
<td>Summary/Overview/Trends—Opportunities; Topics for Further Study/Investigation</td>
</tr>
</tbody>
</table>

TABLE 1
Organization of Graduate Course on Combustion for (Chemical-) Synthesis and Materials Processing

*Fall 1997*
the indicated dimensions for the required burner-condenser combination for synthesizing HCl from its elements. These are indeed examples of combustion synthesis—one just has to broaden one’s notion of what is the “fuel” and what is the “oxidizer,” both gaseous in this instance.

1.2 Spray Combustion of S(l) and P(l)
A commercially important two-phase (liquid fuel) example, familiar to many chemical engineers (and going back to early in this century), is the use of a molten sulfur spray combustor as one step in the ultimate production (via the contact process) of the commodity chemical sulfuric acid. The process, which even to this day is an eye-opener to other engineers, involves melting sulfur, spraying the molten sulfur at 420K into a burner with dried air, and burning the resulting sulfur droplets to form the intermediate product SO$_2$(g) (see Figure 3). The resulting SO$_2$(g)/nitrogen stream is first cooled and then oxidized to SO$_3$(g) in a downstream catalytic converter, and the SO$_3$(g) is finally combined with water in an absorber to produce sulfuric acid. This is, and has been for most of this past century, the bread-and-butter technique for making sulfuric acid. As a result, many chemical engineers are quite familiar with the burning of molten sulfur, which may be regarded as an unusual fuel.

A similar example is the combustion of liquid phosphorus for the ultimate production of phosphoric acid in support of agricultural chemicals production. Thus, the burning of such liquid fuels, ‘weird’ from the viewpoint of traditional combustion engineers, has been part of the tradition of chemical synthesis using combustion techniques for a long time.

1.3 Acetylene Synthesis via the Combustion-Driven Pyrolysis of CH$_4$(g)
An important technique for making acetylene (about one Mt/y, worldwide) is really a rich preheated, premixed vapor combustion process. The 1.4 atm vapor mixer-reactor is shown schematically in Figure 4. Some of the hydrocarbon vapor (here, methane) is sacrificed (burned) to produce high temperature methane-rich gas. The surviving methane is then pyrolyzed to form acetylene, ethylene, soot, etc., in a small plug-flow reaction space downstream of the block of flame stabilizers, prior to a water (or oil) quench. With about 1-ms mean residence time at about 1800K, an acceptable yield (about 24 wt pct. of the hydrocarbon feed) of acetylene is achieved. Unfortunately, soot is an inevitable by-product (about 5% yield), but acetylene is the principal goal. This particular example is also useful to illustrate the principles governing flame stabilization (i.e., what does it take to design a device that avoids extinction by blow-off, or potentially dangerous flashback of these rich preheated/mixed gaseous flames on such multi-hole, water cooled burners?).

1.4 Acetylene Synthesis via a “Submerged Flame” in Crude Oil
There is another interesting partial combustion method for making acetylene at about 10% yield using pressurized oxygen gas bubbling through hot liquid petroleum (crude oil), i.e., the so-called “Submerged Flame” (also BASF) reactor. In contrast to ordinary liquid fuel spray combustors, in this class of reactors the (difficult to atomize) liquid fuel/feedstock is the continuous (not dispersed) phase!

1.5 O$_2$(g) or N$_2$(g) Generation from Decomposing Inorganic Solids
There is yet another important class of combustion-synthesis gas generators that should be mentioned here: those using the exothermic decomposition of an unstable solid compound to generate the desired gas. One such example is a type of oxygen generator used in many current aircraft. To design such a system, an appropriate oxygen-containing compound (here, NaClO$_3$(s)) must be selected, formulated, packaged, and ignited on demand. Of course, the resulting dust-free oxygen must also be produced-released-delivered.
in a reasonable length of time. In this case the ignition process involves the sudden mixing of a fine iron powder with the sodium chloride. When the second main O2 generator (based on the electrolysis of waste water) on the Russian Mir space station failed (August 5, 1997), the crew was forced to rely on “chemical” O2 from canisters filled with lithium perchlorate, some 70 of which were kept on board for just such an occasion. Earlier, the failure of one such canister (in February, ‘97) had caused a smoke-fume emergency for the astronauts on board.

A generically similar and commercially important example is the so-called automotive airbag system, which also served as the basis for several instructive student calculations related to boundary conditions\(^1\) and ignition. This is a compact device in which sodium azide, NaN\(_2\)(s), an unstable solid compound rich in the element nitrogen, is ignited in response to the vehicle deceleration. The decomposing solid propellant, which also contains an oxidizer (e.g., about 30 wt. pct. KClO\(_3\)(s) or NaN\(_3\)(s)) generates the hot nitrogen gas that inflates-deploys the bag in the automobile cabin, thereby protecting the onrushing passenger. Providing automotive air bags (front and side) that are safe and environmentally friendly is a large and growing industry around the world. Indeed, companies prominent in the automotive airbag inflator business are or were chemical-propulsion oriented (solid propellant) companies.

**SECTION 2**

**Combustion Synthesis of Fine Particles and Coatings**

### 2.1 Carbon Black, Fumed Silica, Titania Pigment, TiB\(_2\)(s) Nano-Spheres

Combustion is now routinely used to generate ultra-fine particles (e.g., pigments, adsorbents, or viscosity modifiers\(^8\)). These are frequently particles with remarkably high surface area per unit volume or mass, i.e., their constituent spherules are very small. Carbon black and ordinary soot are comprised of aggregates with spherules only tens of nanometers in diameter, so that the corresponding area per gram is hundreds of square meters! Carbon black is used as a pigment or as an additive to improve wear characteristics (e.g., synthetic rubber tires). Of course, optimizing the nature of the carbon black (surface chemistry and morphology) depends on the specific application, and involves controlling the surfaces of the carbon particles themselves.

The titania industry mentioned above is also a mature one, with the original chloride-process patents going back to DuPont in the 1940s. In the case of titania pigment processes, the feed is usually impure TiO\(_2\)(s) (rutile ore). This is chlorinated in the presence of coke to generate titanium tetrachloride vapor on site using chlorine vapor in a fluidized bed reactor. This titanium tetrachloride is ultimately fed to an oxidation or hydrolysis reactor that is frequently the hot-oxygen effluent of a high-pressure, turbulent, liquid hydrocarbon fuel-lean spray combustor in co-flowing oxygen (with, perhaps, water vapor added). In the tandem turbulent mixer-reactor, one oxidizes the titanium chloride, and nucleates/grows the titanium oxide particles. For pigment particles there must be enough residence time in this reactor (and in downstream tubing) to grow the coagulating particles into the pigment size range (spherule diameters roughly equal to the wave length of visible light).

Much of the titania marketed around the world is made by this chloride process—incrementally improved on a continuing basis but apparently hard to replace with a more economical alternative. What differs from company to company are such details as what the quality of the input rutile must be, what additives are used to control the coagulation process, and how to control the bond strength between the primary particles, etc. It remains to be seen whether the presently accepted concepts of turbulent mixing and particle production in turbulent non-premixed flows can be used to provide useful predictions of the resulting size distribution and evolution of particles in these complex environments. Incidentally, this is another illustration of where, because of the demands of industrial productivity, suspended particle mass fractions are not negligibly small (in many environmental applications of aerosol science, particle mass fractions are less than 0.1 pct.). As in the case of the optical wave guide application\(^9\) described briefly below (Section 2.2), the mass fraction of the particles being produced and collected is appreciable (about 25 wt. pct.).

The most recent International Combustion Symposia contain several interesting papers on gas phase combustion methods to synthesize valuable condensed products.\(^11\) For example, DeFaux and Axelbaum\(^12\) describe a method for producing coated nano spherules of titanium diboride using a co-flowing vapor axisymmetric burner for reacting sodium vapor with a mixture of titanium tetrachloride and boron trichloride, with argon serving as the carrier gas. The sodium chloride subsequently condenses on the TiB\(_2\)(s) particles, in effect preventing the spherules from binding tightly together. These sodium chloride coatings can then be dissolved away in a post-processing step.

### 2.2 Doped Glass Microdroplets for Optical Waveguide Fiber Synthesis

Currently used processes for making continuous optical wave guide glass fiber (see Figures 5a, b, next page) also make use of combustion-generated particles. In such cases, the burner frequently uses methane or hydrogen fuel. The oxy-fuel flame is “doped” not only with a precursor of silica, but also phosphorous-, germanium-, and boron-containing vapors. Such seeded flames produce a high temperature mist of doped silica submicron droplets. By controlling the (phosphorus, germanium, boron, etc.) dopant flow rates, one can control the refractive index of the resulting particles and, by gradually changing the ratios of those dopant compounds in the burner, one can produce microdroplets with different refractive indices. These deposit at different depths in a
cooler preform to produce a porous glass deposit with a built-in refractive index gradient. This soot preform is then pulled through a furnace to produce kilometers of OWG fiber, about 125 µm diameter. Not surprisingly, there are several variants of this process around the world. The particular one sketched in Figure 5a is essentially the Corning method. Nippon Telegraph uses a version (Figure 5b) in which the preform is spinning and pulled vertically through a furnace. One (or more) burner(s) produces and deposits the particles on the end of the withdrawn target (as opposed to the Corning process, where the burner basically moves back and forth relative to the spinning but otherwise fixed preform). An interesting feature of this class of applications is the simultaneous role of high particle mass loading and submicron particle transport dominated by the “non-Brownian” mechanism of thermophoresis.[10,15]

2.3 Combustion Synthesis of Diamond Films
Since the startling report of Hirose,[16] combustion has also been used to grow high-quality diamond films on hot (about 1200K) substrates, even at one atmosphere pressure! Whereas thermodynamically, this result was certainly not anticipated, it turns out that within a narrow range of flame stoichiometry and substrate temperatures one can grow about 20 micrometer crystallite-sized polycrystalline diamond films at rates up to about 200 µm/h from, say, low-pressure rich acetylene/oxygen flames. This is apparently because such flames contain large concentrations of methyl radicals and atomic hydrogen—but diamond films can be grown even if one just generates (via electrical discharge or laser-heated graphite) C atoms or C₂ molecules. Not surprisingly, the interfacial chemical kinetics are not fully understood. But the combustion method is simple and has been used to obtain rapid diamond film growth rates with areas up to about 100 cm² on the substrates Si, Mo, Al₂O₃, and TiN.[17]

2.4 Combustion Synthesis of Fullerenes and “Nano-Tubes”
Combustion (e.g., premixed O₂/benzene at 100 torr) has also been used for synthesizing the so-called Buckminsterfullerene molecule: C₆₀—a polyatomic carbon “soccerball”.[18-20] With a diameter of only 0.71 nm, each of these objects can be regarded either as a high molecular weight “vapor” molecule (see Section 1), or as a “nano-particle” (this Section). In 1996, research quantities of C₆₀ were selling for about 0.1 MS/kg. While the mechanisms of flame-generated C₆₀, C₇₀, and soot-formation may have some features in common, optimum C₆₀ yields (reported to be of the order of 0.5 wt. pct. of the fuel carbon) appear to require both high temperatures (more than 2100K) and low pressures, and the chemical route to C₆₀ appears to require the formation of vibrationally excited poly cyclic aromatic hydrocarbon (PAH) molecules containing 5-member rings.[18] Recently, close-packed bundles of carbon nanotubes have been synthesized using the laser ablation of graphite. Each such nanotube is a sheet of hexagonally bonded carbon rolled up into a seamless cylinder, capped at both ends with semi-fullerene molecules! It remains to be seen whether controlled combustion techniques can be developed to economically synthesize such interesting structures.

SECTION 3
Synthesis of Monolithic Solids via Combustion of Powders
3.1 Self-Propagating High Temperature Synthesis (SHS)
Unconsolidated powder blends (e.g., Ti(s) + 2B(s), or Ti(s) + C(s)) can be ignited at one end to form blocks of useful but somewhat porous ceramic materials (e.g., TiB₂(s) or TiC(s)) by a method sometimes called a “solid flame,” “gasless combustion,” or “self-propagating high temperature synthesis” (SHS).[21,22] Indeed, SHS (investigated extensively in Russia since 1967[23]) is sometimes (erroneously) thought to be the principal application of combustion to materials synthesis. This thermite-type process has also been used for welding materials together, often in the field, and (with the help of centrifugation) for putting refractory coatings on the inside of large cylindrical pipes. Not surprisingly, wave propagation speeds, often of the order of centimeters per second, are system-specific and powder-grain-size dependent. Only now are mechanistically realistic flame theories being developed and applied to these pseudo-premixed flame propagation problems.

3.2 Other Examples of Solid Combustion Synthesis
Garnet luminescent phosphors with submicron particle size for, say, field-emission displays (television screens, etc.) can be synthesized by combusting powders, although the mode of combustion is not self-propagating and the product may itself be a powder (e.g., Eu²⁺-doped Y₂O₃ phosphors via the reaction of metal nitrates (oxidizer) with organic fuel (urea, carbohydrazide, glyoxal) at 773K[24]).
SECTION 4
Combustion for Materials Processing (MP)

Materials synthesized by many other techniques are often modified (upgraded) using some form of combustion device. Several interesting examples are outlined below, with emphasis on more recent or, perhaps, less familiar cases.

4.1 Combustion-Driven “Guns” for Depositing Coatings

Figure 6 (schematically) shows a steady flow particle accelerator based on liquid-fueled rocket combustor technology. This so-called jet (J-) gun is really a miniature liquid-propellant rocket motor except that for a real rocket motor (whose purpose is a compact thruster), one might select liquid oxygen (LOX) as the oxidizer and operate at chamber pressures far in excess of 9.2 atm. But in a ground-based laboratory for coating, say, turbine parts, one can use gaseous oxygen from cylinders. This oxygen and some convenient liquid fuel (here kerosene) are fed into a small water-cooled moderate-pressure combustion chamber-nozzle combination, for the purpose of creating a supersonic exhaust jet of hot gaseous combustion products. This jet is used to accelerate (to about 1 km/s) and heat the powders put into suspension, e.g., 20-µm diameter tungsten carbide. Particle impaction on the target placed downstream results in the desired coating (e.g., thermal- or erosion-barrier, perhaps 250 µm thick). These high-velocity oxy-fuel (HVOF) coating devices are not terribly energy efficient—they heat up a great deal of water, but they accomplish their purpose (adding value to the target) at an acceptable total cost. Several student exercises were developed to address the optimum conditions for accelerating and heating such particles. With a typical system, including the jet gun itself, a powder feeder, a tank of liquid fuel, and oxygen gas cylinders, it is possible to coat a wide variety of materials placed immediately downstream in the rocket-particle accelerator exhaust.

A rather different type of combustion gun, which is intermittent, is the detonation (D-) gun (see Figure 7). Here, repetitive H₂(g)/O₂(g) detonations are propagated through a suspended powder and each detonation wave acts like a piston to propel the hot particles onto the workpiece. This process is repeated about every 1/6 of a second. Praxair (formerly Union Carbide) Surface Technologies has a proprietary coating business based on the D-gun. This device is an excellent vehicle to teach the theory of detonations—viz., supersonic combustion waves that produce high pressures and temperatures behind them. Accordingly, they are capable of heating and accelerating particles suspended in the combustible gas mixture. Note that the pressure vessel is, indeed, like a gun barrel—with repetitive spark-ignited oxy-hydrogen detonations that shoot each fresh charge of suspended particles out onto the target. Using the principles of detonation theory, and the heat/momentum/mass transfer properties of the suspended particles, each engineering student can go through the steps of designing such a gun. This includes sizing, determining how rapidly it can be fired and reloaded, what kind of coating rates are achievable, etc. These are instructive, yet conceptually simple, calculations for engineering students.

The reader probably already suspects that it is possible to carry out many types of explosive processing for the cladding or (re-)shaping of materials. For example, to clad one material onto the surface of another (substrate) without the need for a huge mechanical press, it is possible to assemble a sandwich of the ingredients on an anvil, with a sheet of solid propellant above the cladding material (see Figure 8). Upon igniting the solid propellant, a propagating detonation slams these two materials together. Many controlled explosive procedures of this type are being used for cladding, shaping, or sintering materials, including powdered metals.

4.2 Combustion-Driven Cutting or “Gas” Welding Operations

Most engineers are already familiar with the fact that gaseous acetylene/oxygen flames are hot enough (about


We also demonstrated that with simple rate-controlling postulates, it is usually possible to estimate the size and performance of the required equipment. Needless to say, in any particular case, this would be the logical first step before

CONCLUDING REMARKS

Other important CS/MP examples were used in the course, including (for the MP segment) combustion-driven spray drying of ceramic slurries and submerged burners for heating aggressive molten baths. But the particular examples selected above will be sufficient for our present introductory purposes. In principle, the instructor will have little difficulty finding yet others, perhaps better suited to the background of an individual class. Unfortunately, however, there is not yet any coherent account of this overall subject that can be used as a textbook for a CS/MP course—a situation that motivates the writer to embark on this project. Useful information on many of the individual chemical processes included here can be found in the chemical engineering encyclopedias: Kirk-Othmer and/or Ullmans. But, of course, proprietary details are, at best, found only in the patent literature. For the underlying transport and combustion principles, the situation is much better—for this course I simply used my review papers, Rosner and Papadopoulos, and the 3rd printing of my 1986 textbook Transport Processes in Chemically Reacting Flow Systems, which most Yale students already had. (A second edition should be available, with additional CS/MP content, by 1998-9.) Other recent, readable accounts of the fundamentals of combustion were put on reserve in the Engineering Library.

Pedagogically, for teaching the principles of thermodynamics, chemical kinetics, gas-dynamics, mixing, chemical reactor design, detonations, materials science, etc., engineering students from many disciplines can relate to the practical yet extraordinary examples above. They transcend the traditional power generation/propulsion combustion topics and are, accordingly, appealing to broaden our perspective. Indeed, for graduate students, many of these examples will also suggest interesting, perhaps hitherto intractable, research projects that probably could be tackled now. I hope these representative examples convince the reader once and for all that combustion is not limited to power generation/propulsion or process heat, and that there are many both mature and/or evolving technologies in which combustion can be used to produce very valuable materials (in some cases worth thousands of dollars per kilogram). This class of combustion applications also forces the engineer to broaden his or her conception of what is a useful fuel and what is a useful oxidizer, and to consider contacting and mixing configurations that are, more often than not, rather different from the canonical ones displayed in most combustion textbooks.

It is also evident from these CS/MP topics that if you are trying to optimize a combustion reactor process for, say, diamond film growth, you would be well advised to team up with materials scientists who can characterize such deposits and the prepared substrate, flame chemists, and experts in flame aerodynamics and transport phenomena. Thus, while chemical engineers are in an extraordinarily strong position to contribute, an interdisciplinary attack will probably be essential for success in the CS/MP arena.

As summarized above, in this graduate course we considered interesting practical examples where further combustion research may, in fact, make combustion the most attractive route to synthesizing and/or processing valuable new materials, rather than (as is sometimes the case) a cheap but still poorly understood or controlled alternative.

We also demonstrated that with simple rate-controlling postulates, it is usually possible to estimate the size and performance of the required equipment. Needless to say, in any particular case, this would be the logical first step before

3500K at 1 atm) and compact enough to provide local work-piece heat fluxes (more than 3 MW/m²) adequate for cutting or welding operations on metal sheet materials. Indeed, by combining the principles of turbulent jet mixing and convective heat transfer with a steady-flow energy balance, engineering students can make useful estimates of torch requirements and attainable cutting or welding rates (crucial topics often not even present in handbook accounts of these operations). Perhaps less familiar is the fact that after localized work-piece heat-up, for several important metals (including iron and titanium alloys) the fuel supply can actually be cut off completely and metal combustion (with molten metal oxide runoff) alone will continue the cutting operation! This cutting technology, in which an acceptably small fraction of the workpiece becomes the fuel, is not new (Air Products Corporation was supplying such O₂(l) lances in 1941 and such an example is shown in the introduction of Spalding’s convective mass-transfer textbook, but this type of microjet “oxygen lance cutting” certainly deserves attention in this short CMP-review.

4.3 Surface Treatments: Flame Polishing, Spheroidizing, etc.

Another noteworthy MP example in which combustion is conveniently used is surface (fire-) polishing. For example, could you predict how long it would take to smooth an initially rough metal or ceramic surface by the mechanism of surface-energy (curvature) driven surface diffusion using a high temperature torch? Can you design an economical process using hot combustion products to spheroidize a powder that presently has poor flow characteristics because of irregular grain shape?

Changing near-surface compositions (hence properties) by metal workpiece exposure to tailored combustion-product environments (e.g., containing ammonia, devoid of SO₂, CO₂, and H₂O, etc.) is also a widely used technique for the nitriding, carburizing, carbo-nitriding, etc., of ferrous and nonferrous metals. Many of these practical examples can be used to teach the principles of transient one-dimensional Fickian solute diffusion. This includes calculations of the required process time at temperature, again without recourse to proprietary (black-box) computer codes.
going to more elaborate, often proprietary or black-box, computer models. In the writer’s opinion, from a pedagogical point of view, this is a healthy and confidence-building orientation for engineering students, too often neglected. Moreover, to design processes that are intrinsically novel, chances are that the packaged programs commercially available do not anticipate the circumstances of present interest!

To conclude, many readers will appreciate that there are also many attractive research topics lurking among these lines. I commend them to your attention as viable and healthy directions for combustion research to take in the future.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the helpful comments and feedback of P. Benedek, K. Brezinsky, H.F. Calvate, J.B. Fenn, A. Gomez, M. Frenklich, I. Glassman, S.A. Gokoglu, J.L. Katz, M.K. King, A.G. Konstandopulos, S.E. Pratsinis, R.C. Tucker, Jr., and G.D. Ulrich on some of these synthesis/materials processing facets of combustion engineering. The author’s CS/MP research is carried out at the Yale Center for Combustion Studies and the Yale High Temperature Chemical Reaction Engineering (HTCRE) Laboratory.

REFERENCES

3. Sigri Elektrographit GmbH product literature
AN EXPERIMENT IN COMBUSTION

KEITH B. FORDON, ANTONIO M. VINCITORE, SELIM M. SENKAN
University of California • Los Angeles, CA 90095

In modern chemical engineering, environmental issues contribute significantly to process design and operation. Consequently, curricular changes must be made to incorporate new approaches and examples that illustrate concepts related to the protection of the environment.

Combustion is an excellent example of applied high-temperature reaction engineering where thoughtful compromises should be made between pollutant formation and power generation. Combustion is also a widely used process, with applications ranging from space heating to automotive and air transportation, and is the major contributor to air pollution. Consequently, students can easily relate to many environmental issues associated with combustion technologies—for example, the formation of nitrogen oxides (NOx) and soot.

While senior chemical engineering students are well aware that the oxidation of hydrocarbon fuels produces carbon dioxide and water as the major products, however, they are not familiar with the fact that hundreds of trace by-products are also routinely formed in combustion and that combustion conditions cannot simply be altered to minimize the emission of all pollutants. In Figure 1, the levels of thermal NOx and hydrocarbon by-products formed in combustion are presented as a function of fuel-air equivalence ratio. Equivalence ratio, \( \phi \), is defined as the actual fuel/air ratio used divided by the fuel/air ratio corresponding to stoichiometric conditions:

\[
\phi = \frac{(\text{fuel/air})_{\text{act}}}{(\text{fuel/air})_{\text{stoch}}} 
\]

Figure 1 shows that NOx emissions formed as a consequence of the reactions of N2 exhibit a maximum near stoichiometric conditions due to high flame temperatures and decrease rapidly at higher and lower equivalence ratios when temperatures decrease because of the presence of excess fuel and air, respectively. Lower temperatures, however, reduce reaction rates and result in the emission of unburned hydrocarbons from combustion systems. Consequently, careful compromises must be made between NOx and hydrocarbon emissions.

When heat recovery is necessary, such as in heaters and boilers, a section of the combustion device is operated under fuel-rich conditions to promote radiative heat transfer from gases. The fuel-rich stage is then followed by a fuel-lean stage in order to fully oxidize unburned hydrocarbons. This “two-stage” combustion is widely used today to minimize both thermal NOx and hydrocarbon emissions.\(^1\) In addition, control technologies, such as catalytic converters, may also be required to meet emissions standards.

Among the hydrocarbons emitted from combustion processes, polyaromatic hydrocarbons (PAH) are of particular concern due to the potential mutagenicity and carcinogenicity of some of their isomers.\(^2\) PAH are also believed to be precursors to soot, the formation of which represents a loss in combustion efficiency and is a significant environmental problem by itself. Although PAH are emitted at trace levels, on the order of parts per billion by volume (ppbv) to parts per million by volume (ppmv), they often represent the greatest health risk associated with combustion systems.\(^3\) Therefore, the development of combustion technologies and/or operation strategies that will reduce these emissions, together with NOx emissions, continues to be of significant practical interest.

Combustion devices generally operate under conditions in which the oxidizer (air) and fuel are not mixed prior to

Keith Fordon is a development engineer in the Department of Chemical Engineering at UCLA. He earned his BS with honors in chemical engineering from UCLA in 1993.

Antonio Vincitore is a PhD candidate in the Department of Chemical Engineering at UCLA. He received his BS in chemical engineering from Manhattan College in 1992. His research has been focused on PAH formation in hydrocarbon flames.

Selim Senkan is Professor of Chemical Engineering at UCLA. He received his BS from METU, Turkey, and his MS and PhD from Massachusetts Institute of Technology. His research interests are in chemical reaction engineering, combustion, and laser diagnostics.
reaction. Consequently, diffusion flames dominate the mode of burning. At UCLA, we implemented an opposed jet burner system that mimics the diffusion flames encountered in practical combustion devices. In this system, the oxidizer and fuel move in an opposed flow configuration, whereby the combustion reaction occurs in a flat flame near the stagnation plane. Because this flow field has a central axis of symmetry, the quantitative chemical composition of the flame can be readily determined by withdrawing samples along the central longitudinal axis of the burners.

Prior to the experiment, students attend lectures that emphasize the effect of fluid dynamic residence time and mixing on pollutant formation within diffusion flame structures, coupled with a fluid dynamic analysis of the Navier-Stokes equations describing the flow field encountered in the opposed flow experiment. In addition to a discussion of the relevant transport phenomena, various chemical pathways, such as those involved in the formation of benzene and PAH, and in the oxidation of methane to carbon monoxide, are reviewed. For example, students are introduced to both “even” and “odd” number carbon reaction pathways that lead to the formation of aromatics within hydrocarbon flames. The following even-number carbon pathway describes the formation of the first benzene ring at low temperatures:

\[
\begin{align*}
C_2H_2 + C_2H_3 &= n - C_4H_5 \\
C_2H_2 + n - C_4H_5 &= C_6H_6 + H
\end{align*}
\]

where \(C_2H_2\) is produced as a result of a sequence of dehydrogenation reactions, such as

\[
\begin{align*}
C_2H_6 + H &= C_2H_5 + H_2 \\
C_2H_5 &= C_3H_4 + H \\
C_2H_4 + H &= C_3H_3 + H_2 \\
C_3H_3 &= C_3H_2 + H
\end{align*}
\]

In the odd-number carbon reaction route, benzene has been proposed to form via

\[
C_3H_4 + C_3H_3 = C_6H_5 + H
\]

followed by the hydrogenation of the phenyl radical

\[
C_6H_5 + CH_4 = C_6H_4 + CH_3
\]

The \(C_3H_3\) radicals are produced by the addition of a singlet methylene radical, \(CH_2(8)\), to acetylene:

\[
CH_2(8) + C_2H_2 = C_3H_3 + H
\]

Similar pathways for the formation of PAH are also reviewed. At the end of a two-week work period, students write a final report discussing the effects of fluid dynamics, fuel structure, dilution, and other process conditions on the formation of pollutants in hydrocarbon flames. They also present their work orally in front of other groups and selected faculty.

**THE EXPERIMENT**

An illustration of the experimental burner system and sampling configuration is shown in Figure 2 (next page). The flame was stabilized between two opposed 1.0-inch I.D. burner ports. The flows of oxidizer and fuel gases were regulated using mass flow controllers. The oxidizer stream was introduced through the top burner port and the fuel stream was introduced through the bottom burner port. Argon diluent was used in the fuel stream to control the flame temperature. The flame was protected from ambient air by an argon shield gas. The shield gas also aided in cooling the hot combustion products. All gases were vented through the water-cooled heat exchanger that was built around the bottom burner. The arm supporting the top burner was similarly water-cooled (not shown).

In the present experiment, the distance between the burner ports was 1.8 cm, the oxidizer stream was air at a flow rate of 5.8 L/min, and the fuel stream was a \(\text{CH}_4/\text{Ar}\) mix (75% by volume \(\text{CH}_4\) and 25% by volume \(\text{Ar}\)) at a flow rate of 4.0 L/min. This corresponds to an overall equivalence ratio significantly greater than one \(\phi = 4.9\). We chose this condition to increase the emission of products of incomplete combustion from the burner system.

Visually, the flame exhibited blue, luminous yellow, and dark orange zones characteristic of a diffusion flame, with the flame being positioned on the oxidizer side of the stagnation plane, as illustrated in Figure 3 (next page). Since oxygen was the limiting reactant, methane necessarily diffused across the stagnation plane into the oxidizer side. The blue zone marked the occurrence of reactions associated with stoichiometric flames. In addition, a dark zone, located be-
tween the blue and luminous yellow zones, was noted by the students during the experiment. The luminous yellow and dark orange zones indicated the presence of higher molecular weight hydrocarbons and the formation of soot particles or precursors.

Samples were withdrawn via a heated quartz microprobe having a 100 µm orifice at its tapered tip and transported through a silica-lined, stainless steel transfer line to the Hewlett-Packard (HP) 5890 II gas chromatograph (GC). Light gases were separated by Hayesep DB and Hayesep T packed GC columns and detected with a thermal conductivity detector (TCD). Heavier gases were separated by an HP-5MS capillary column and detected with an HP 5971A mass selective detector (MSD). The entire sampling system was maintained at 300°C and subambient pressure to minimize the adsorption of PAH with five rings or less. Mole fraction profiles were generated by moving the entire burner assembly relative to the fixed sampling probe. Temperature measurements were made in a similar fashion with a silica-coated 0.15 mm Pt-13%Rh/Pt thermocouple.

SAFETY

This experiment presents obvious safety concerns. High flame temperatures (1200°C) and sampling system temperatures (300°C) must be handled with extreme care. The fuel gas used is flammable, and poisonous by-products such as CO are produced. Therefore, many safety features have been incorporated into both the design and the construction of the experimental facility and student operating procedures.

Contact with the burners or the sampling line must be avoided during the course of the experiment. The surface temperatures of the burners were kept sufficiently low by both the shield gas and water cooling. The sampling line was insulated. Although the combustion products were vented through the bottom burner, an overhead fume hood was constructed on top of the experiment to increase safety. As a final safeguard, a carbon monoxide detector was installed.

With the potential hazards in mind, an experienced teaching assistant checks the oxidizer and fuel flow rates before the flame is lit. In addition to the mass flow controller displays, rotameters were installed to provide further visual indication of the flow rates. The flow of both oxidizer and methane can be ceased at any time with manual shut-off valves. Students are taught the safe start-up and shutdown procedures. Gas flows must be turned on sequentially in the following order: the fuel-side Ar, the Ar shield gas, the air, and finally the methane. Following each flame sampling, the gas flows are turned off (i.e., the flame is extinguished) in the reverse order.

A routine problem that has been encountered is a flaring of the flame immediately after lighting, due to an imbalance between the total flow rate and the venting flow rate. If the appropriate adjustments cannot be made quickly, students are instructed to use the manual shut-off valves to shut off the methane first, then the air, and then to set the mass flow controllers to a setpoint of zero flow rate so that a hazardous situation does not arise upon future start-up. To avoid an accident, students are instructed to immediately alert the teaching assistant (who is always present) of any equipment malfunction or unusual sight or sound. They are also trained in the correct evacuation procedure from the laboratory should this be necessary.

In spite of all these precautions, the active presence of a knowledgeable and experienced teaching assistant is im-

Figure 2. Experimental set and sampling configuration.

Figure 3. Visual characteristics of an opposed flow diffusion flame.
perative to the safe operation of this experiment.

DATA ACQUISITION AND ANALYSIS

The mole fraction profiles for a total of thirty chemical species, ranging from major components to trace aromatics and PAH, were determined in experiments that lasted from four to five hours. This represents the analysis of approximately ten samples withdrawn from the flame, which is typically adequate to discern trends in the species mole fraction profiles. Major components are defined as CH$_4$, Ar, O$_2$, N$_2$, CO, H$_2$, and H$_2$O and were all detected with the TCD and quantified with calibration standards.

Figure 4 shows the chemical structure and summarizes the method of quantification for each hydrocarbon product and by-product species detected in the flame. The species that were detected with the MSD, with the exception of vinylacetylene and benzene, were quantified with the ionization cross section method. This method provides mole fractions that are accurate within a factor of two. The accuracy of the mole fractions of species that were quantified using calibration standards was estimated to be ±15%.

The fluid dynamic strain in the flame as set up by the opposed flow field was calculated as an illustration of residence time constraints. The strain rate, $K$, is defined as the axial velocity gradient on the oxidizer side of the stagnation plane. Mathematically, $K$ is defined as

$$K = -\frac{du}{dz}$$

where $u$ is velocity and $z$ is displacement along the axis connecting the centers of the burner ports. Since the above expression requires knowledge of the actual flow field, which was not available, the strain rate was calculated using the following expression that requires only observable quantities:

$$K = \frac{-2u_o}{L} \left(1 + \frac{u_f}{(-u_o)} \frac{\rho_f}{\rho_o}\right)$$

where $L$, $u_o$, $u_f$, $\rho_f$, and $\rho_o$ are the distance between the burner ports, the oxidizer port outlet velocity, the fuel port outlet velocity, the fuel stream density, and the oxidizer stream density, respectively. With the assumption of plug flow (ensured by a network of screens) and using the experimental conditions given earlier, this corresponds to
a computed strain rate of 34 sec⁻¹ at 298 K. This is a relatively low value when compared to the extinction limit of CH₄, suggesting a high residence time within the flame, which should lead to the production of measurable quantities of PAH. The maximum mole fractions of the product species detected in the flame is presented in Figure 5.

**SPECIES MOLE FRACTION PROFILES**

Mole fraction profiles for the major species, together with the temperature profile, are shown in Figure 6. The temperature profile shows a maximum temperature of 1200°C at a distance of 6.5 mm from the fuel port. The flame temperature exhibited a nearly linear variation from each burner port to the point of maximum temperature, which is in good agreement with the literature.¹³

The results for the major species mole fraction profiles compare well with the work done in previous diffusion flame studies.¹³¹⁴ As can be seen in Figure 6, both CH₄ and O₂ were largely consumed at about 7 mm from the fuel port, near where the maximum flame temperature was observed. A significant, yet relatively small, amount of O₂ penetration into the fuel-rich portion of the diffusion flame was noted, however. The mole fraction of CO increased as the fuel was consumed and exhibited a peak mole fraction of 0.035 at 6 mm, followed by a decrease with increasing distance from the fuel port. Hydrogen followed the same trend as CO with a maximum mole fraction of 0.014 at 5.5 mm. The mole fractions of CO and H₂ both exhibited maxima on the fuel-side of, and near to, the point of maximum heat release (maximum flame temperature), consistent with the transition from fuel-rich to fuel-lean flame chemistry. Carbon dioxide and H₂O mole fraction profiles followed a pattern similar to CO and H₂ and exhibited maxima at about 7.0 mm from the fuel port, also close to the point of maximum flame temperature. These results are indicative of the occurrence of the highly exothermic oxidation reactions, CO + OH = CO₂ + H and H₂ + OH = H₂O + H.

In Figure 7, the mole fraction profiles for species ranging from butadiene to PAH are presented. These species were selected to illustrate the wide range of hydrocarbon pollutants that can be formed in combustion processes. As can be seen in the figure, benzene was by far the most abundant of the aromatic species produced, with a peak concentration of about 77 ppm at 4-5mm. All hydrocarbon species exhibited a sharp decrease in concentration at 7 to 7.5 mm from the fuel port, corresponding to the transition from fuel-rich to fuel-lean flame chemistry created by the competition between gas-phase polymerization and oxidation reactions, respectively.⁵⁻⁷ Some of the PAH detected, presented in order of abundance, were naphthalene, pyrene, phenanthrene, and cyclopenta(cd)pyrene. Naphthalene appeared in greater concentration than any of the other PAH, reaching a maximum level of 7.4 ppm. These results are in excellent agreement with previous studies¹³¹⁴ and are consistent with those in premixed flames.¹¹¹

Future plans involve development of the capability to simultaneously measure PAH and NOₓ emissions. This way, students will be able to readily observe the intimate connections that exist between flame temperature, overall equivalence ratio, dilution, and NOₓ and PAH emissions.

**CONCLUSIONS**

The opposed jet diffusion flame provides a convenient laboratory tool to illustrate fundamental environmental chemical engineering principles associated with combustion. These experiments strengthen students’ engineering knowledge and skills, concomitant with exposure to the use of sophisticated

---

**Figure 5.** Maximum mole fractions of product species detected in the experiment.
 instrumentation and the detailed chemistry innate to combustion systems. To make it a valuable and rewarding experience for students requires faculty with research interests in the area of combustion to provide in-house expertise and future generations of experienced teaching assistants who are seasoned in the associated theory and experimental and safety techniques and procedures.

We have demonstrated that a large variety of potentially toxic by-products are formed in the combustion of simple hydrocarbon fuels. Of the 26 product species detected, 12 are either explicitly or implicitly listed as "hazardous air pollutants" in the Clean Air Act Amendments of 1990.[16] The measurement of a large variety of pollutants made an impact on the undergraduates who participated in this experiment, as they were able to better appreciate the complexity and breadth of modern environmental issues.

ACKNOWLEDGMENTS

This experiment was made possible by funds from the Texaco Foundation. The authors also would like to thank Dr. Marco J. Castaldi for his valuable contributions. The undergraduate students who participated in the first-ever laboratory course run of this experiment (Fall Quarter, 1995) were Tadashi Allen, Jennifer Bradford, Vincent Chan, Chung-Yuan Chiang, Darryl Dunn, Yousun Kim, Ria Momblanco, Tanya Sacay, Danilo Vukovic, and Tim Wang.

REFERENCES

PROCESS INTEGRATION AND INDUSTRIAL POLLUTION PREVENTION
Merging Theory and Practice in Graduate Education

GIORGIO CARTA, M. DOUGLAS LEVAN,1
H. DENNIS SPRIGGS,2 GREGORY A. CLEOTELIS, II,3 JAMES E. RYAN, JR. 4
University of Virginia • Charlottesville, VA 22903-2442

Pollution prevention and process integration are highly consistent concepts in chemical manufacturing. Pollution prevention through source reduction, reuse, and recycle of resources is stipulated by law.1 Process integration is inherently conservation oriented, as it has the primary goal of maximizing the efficiency of design by minimizing the consumption of materials and energy.2 A chemical process in which components are integrated in an efficient system will generally be more economical and will pollute less. Ultimately, our goal in chemical process design should be closed-loop systems with zero emission to the environment, but this goal, of course, has to be balanced against economic factors and other constraints that would normally be encountered in practical situations. This can only come about through the education and training of scientists and engineers who can implement technological advances in designs that integrate regulatory and environmental considerations with the goal of economic development within the constraints of an industrial operation.

A new course, “Process Integration and Industrial Pollution Prevention,” was recently developed at the University of Virginia with the assistance of several experts and with the participation of a company sponsor. The course is offered within the university’s Environmentally Conscious Chemical Manufacturing (ECCM) Program (supported by a Graduate Research Training grant from the National Science Foundation and by a grant from the Academic Enhancement Program of the University of Virginia), which has both research and educational components. Fundamental research is conducted in four major areas: development of inorganic catalysts; development of biocatalysts for chemical synthesis; development of alternative solvents; and development of adsorption processes for separations and energy applications. In each area the goal is to provide a foundation for the conception and development of alternative, environmentally benign technologies.

This graduate course in pollution prevention provides a central focus for both the students and the faculty participat-
Ultimately, our goal in chemical process design should be closed-loop systems with zero emission to the environment, but this goal, of course, has to be balanced against economic factors and other constraints... This can only come about through the education and training of scientists and engineers who can implement technological advances in designs that integrate regulatory and environmental considerations with the goal of economic development...

As a whole, the course is an example of a new approach to graduate education in chemical engineering. It provides an environment where students can learn while simultaneously solving significant industrial problems. This, of course, is always done through the research component of doctoral studies, and that must continue to be the main focus. On the other hand, doctoral research is typically long-term, fundamental work, often remote from industrial applications and almost always conducted in ways quite different from those used in industry for the solution of plant problems. In an industrial setting, short time frames, teamwork, and integration of economic considerations are often dominant issues that are not considered within the typical doctoral research activities. An approach where graduate students are immersed for a time within a practical setting is common in many professional graduate schools, such as business, law, and medicine, but is not often found in chemical engineering. This field, however, could also benefit tremendously from such exposure in ways that could provide avenues for successful partnerships between industry and academia.

**COURSE RATIONALE**

The fundamental premise for this course is shown in Figure 1. An efficient, nonpolluting chemical process is based on technological innovations that are rationally integrated in a system. The “building blocks” (fundamental principles and unit operations) come from research; the “how to assemble” know-how and tools are covered in the course.

There are three main themes:
1. The philosophy of integrated design
2. The tools for an integrated design methodology
3. The application to an actual industrial situation

The underlying philosophy taught in this course is what has been called the “Science of the Big Picture,” or SOTBP, as a simple heuristics set for design that entails the following steps:

*Consider the “big picture first” by looking at the global process as an integrated system*

Use fundamentals at each step to establish a priori targets for design efficiency and the consumption of materials and energy.

Worry about details (later) to finalize the design and support the global view.

The term “fundamentals” here denotes thermodynamics laws and basic mass and energy balances. Virtually all established integrated design methodologies, such as thermal pinch analysis and mass exchange networks, follow this general heuristics set. Following this approach, process design evolves through a series of decisions that provides increasing levels of detail. Each decision will be sound from the overall viewpoint and will be consistent with fundamentals. Details are worked out later, only after the overall structure of the process has been established. Thus, a global understanding of the process is obtained first. Next, methods of structured thinking, including how to decompose the design problem and to apply rules-of-thumb and experience, are used. And finally, simulations and/or experimental analyses are used in support of fundamental understanding and to complete design details.

The tools reviewed in the course are methodologies for integrated design. The hierarchical review methods of Douglas and others are covered in detail and contrasted to traditional approaches that break down a process into its unit
operation components instead of levels of analysis. The point is made that while breaking the system down into units has been a traditional way of dealing with complex processes, it provides little information about the interconnection of the elements and sheds no light on how these elements should come together to form an efficient process. Techniques for heat and mass integration are also reviewed with an emphasis on visualization techniques as a key to understand the problem, generating solutions, and communicating. Legal and regulatory issues are also covered and are viewed as an integral part of the “big picture” of the pollution prevention problem.

Finally, the application component of the course is an actual industrial project that is developed as an assignment for the students in collaboration with an industrial sponsor. The students are given free rein to solve the problem at hand using any of the tools available and including experimentation. The project has to be conducted within the framework imposed by the industrial sponsor, however.

**COURSE ORGANIZATION AND CONTENT**

The course was team-taught and involved the participation of several experts. Approximately half of the class time was in a lecture format, while the remaining time was spent working on the course project (see Table 1). In the first offering, eleven doctoral students took the class. They were divided into two design teams, each with an appointed team leader. Regular meetings were scheduled with the course instructors.

The course began with an overview of the driving forces at the root of pollution prevention in industry (environmental regulation, product quality and consumer demand, and efficiency and cost reduction), of the industrial obstacles to its implementation (unfavorable balance between long-term environmental benefit and short-term profit, capital requirements, inertia), and of regulatory impediments to pollution prevention (complexity and inconsistency of environmental regulation, regulatory focus on individual media, narrow definitions of pollution prevention).

Next was a detailed coverage of the legal principles of environmental regulation and of regulatory aspects of management strategies for achieving pollution prevention. Four lecture hours given by two practicing environmental lawyers covered the history of modern environmental law, the relationship between federal and state government in the environmental arena, and the common elements of statutory programs such as ambient and performance standards, permit programs, self-reporting requirements, and enforcement tools. The structure of Virginia’s environmental programs (water and air) was also covered as an example. These lectures included an overview of the Pollution Prevention act of 1990 and of ISO 14000 and 14001 standards.

The next set of lectures introduced a general framework for pollution prevention through integrated design. We began by defining design as a multifaceted problem that depends on both “technical” and “nontechnical” factors, including the overall business environment the company operates in, how the design work is organized, and the importance the company places on process design. The key point illustrated here was that pollution prevention is not just a “technical” problem. And, it is not just a matter of management. It is both—which makes it especially challenging. Considerable emphasis was then placed on correctly structuring “the problem.” The instructors’ experience is that engineers, even experienced ones, must be helped to see the big picture first and to fill in the details later. It is a process that must begin with a clear definition and setting of goals: the sponsor’s goals, the goals of the individual participants, and the time-frame within which these goals are to be attained.

The students were challenged to define their own personal goals in this class, pointing out that the ultimate measure of
success might be the actual implementation of the solution proposed for the course project. We made the point that just arriving at a solution is not sufficient—getting the sponsor to appreciate its value and to implement it is part of the job. Thus, we emphasized the need for effective contact with the sponsor as a key to credible, implementable solutions. The next set of two lectures was devoted to a presentation of the course project (described later). Two process engineers from the sponsoring company presented the situation defining the problem, the technical company constraints, and the expectations.

Following this introductory material, a set of lectures was devoted to a review of process integration tools. Students were challenged to view chemical processes as integrated systems such as the one depicted in Figure 2. Our job is to find the most favorable allocation of mass and energy flows that would minimize waste. The first step in the analysis is a hierarchical review of design decisions at different levels of detail. Following Douglas’ work, we made the point that this procedure, originally developed for process synthesis, can also be applied for waste minimization in an existing facility, as discussed, for example, by Rossiter, et al.

In fact, by understanding how waste is generated from decisions made at different structural levels, one can systematically develop retrofit alternatives.

Beyond the hierarchical review approach, two important dimensions of the problem were considered in detail: the creation and routing of chemical species (mass integration or mass exchange networks—MEN’s) and the application of energy (energy integration, or HEN’s). In heat integration we examined tools such as pinch analysis (or pinch technology), mixed-integer nonlinear programming, and simulated annealing that shift the focus away from the heating and cooling of individual streams to the global allocation of energy in an integrated system. Similarly, in mass integration, we examined recently developed techniques that shift the focus away from merely linking unit operations (reactors and separation units) to a global allocation of chemical species by considering the efficient creation of desirable species, the minimization of undesirable components, and the routing of species to their most desirable destinations. A recent monograph by El-Halwagi provided reference material and case studies in mass integration.

Figure 3 shows the generic approach for species allocation presented in this work.

When the overall process is considered, waste minimization targets can be established a priori based on fundamental application of overall balances. This is true for both energy and mass integration. A species allocation diagram similar to that in Figure 3 is drawn for each chemical species (e.g., water in a waste-water minimization problem). The first step is then to consider segregating each “source” or stream containing that species. Often, major waste reduction can be obtained simply by avoiding mixing of process streams and reusing the segregated sources with a direct recycle to the process.

The next step is to consider implementation of a “species interception network” (SPIN) where mass-separating agents are used to upgrade segregated sources to a quality adequate for in-process recycle to appropriate “sinks”—ordinarily unit operations that can use the upgraded sources. Shortcut design methods are used for screening alternatives at this level on the basis of cost estimates and economic potential.

Finally, the last step is to consider manipulation of “sinks” and “generators” so as to reduce the creation of undesirable species and improve their efficiency.
Clearly, a hierarchical level exists in this analysis. Usually, acceptability (and, in many cases, impact) is greatest for simple segregation and direct recycle modifications of an existing process while acceptability, and sometimes impact, is normally smallest for more costly sink/generator manipulations.

In a final set of lectures, we covered quantitative aspects of pollution monitoring and emission inventory and examples of pollution prevention measures based on the work of Nelson. The rest of the semester was spent working on the course project in close collaboration with the industrial sponsor.

**COURSE PROJECT**

The project for this course was suggested by AlliedSignal personnel. It deals with an existing problem concerning copper emissions from an adipic acid manufacturing plant. At a facility in Virginia, AlliedSignal produces about 30 Mlb/yr of adipic acid via the oxidation of a waste stream composed of cyclohexanol and cyclohexanone, which is generated in another process. Figure 4 shows a simplified process flow diagram. The process produces 3,000 to 5,000 lb/h of crystalline adipic acid as well as a bleed stream at a rate of about 2,000 to 3,000 lb/hr that contains water, nitric acid, organic acids by-products (principally glutaric and succinic), as well as copper and vanadium, which are catalysts for the oxidation process. Currently, the bleed stream is neutralized and sent to a regional waste-water treatment plant. The company anticipates that changing waste-water regulations will require the virtual elimination of copper discharges. The following objectives were thus set by the sponsor:

1. Recover copper and vanadium from the bleed stream
2. Recover nitric acid from the bleed stream and recycle to the process
3. Recover the organic acids from the bleed stream

The sponsor specified that the first objective must be accomplished. Objectives 2 and 3 were to be pursued if economically feasible. The sponsor required that the solution should be implementable in an 18-month time frame and that a 35% simple rate of return should be used for economic evaluation. The short time frame precluded most solutions involving changes in the process chemistry that would entail major modifications of the existing adipic acid facility.

The eleven PhD students enrolled in the class were divided into two independent teams that engaged in a friendly competition. Each team conducted its own literature search, visited the plant on several occasions, obtained samples of the bleed stream and other data from the plant, conducted their own experimental investigation, and carried out preliminary design calculations and economic estimates. An initial proposal was to install end-of-pipe treatment devices (ion-exchange columns, membrane systems, electrochemical methods, etc.) that would remove copper from the bleed stream. When the process was analyzed from a global viewpoint, however, these alternatives were quickly discarded since it was recognized that it would be sufficient to recover the organic acids in order to produce an aqueous stream containing copper and vanadium catalysts and nitric acid that could be recycled directly to the process. This required the definition of a waste interception network capable of removing the approximately 400 to 800 lb/hr of glutaric and succinic acid that is produced as a by-product in the oxidation process.

The teams recommended different solutions. One team followed a more traditional approach of esterifying the acids with an excess of methanol and extracting the diesters with an organic solvent. The students initially followed a US patent describing a reactive-extraction process, but then decided to perform their own experimental investigation finding that no-catalyst was required for esterification in the bleed stream and that toluene could be used as an effective extraction solvent. The other team followed a more innovative approach, discovering in the laboratory that, for the conditions of the bleed stream, the organic acids could be extracted into an existing process feedstock. Although the partition coefficient is not as favorable as in the case of extraction of the dimethyl esters, the proposed approach has the advantage that the extraction solvent is a reactant in the process so that no contamination of the existing adipic acid facility with extraneous species would occur. The raffinate, devoid of a large portion of the organic acid by-products, could be recycled directly to the adipic acid process.

Based on preliminary design and economic estimates, each alternative met the sponsor’s objectives. In each case, in addition to virtually eliminating copper emissions, potential sales of the recovered organic acids would provide a substantial economic return. At the conclusion of their work, each team presented their recommendations to the sponsor. This task was made rather challenging by the fact that the presentations took place at the plant and were attended by a large group that included senior plant management, several process engineers, plant operators, environmental officers, and chemists and engineers from the technical support group of the company. The students were asked to meet this challenge with a balanced presentation addressing the diverse audience. The company is now evaluating implementation of one of the two proposals made by the students and is acquiring equipment for pilot-scale testing.

Finally, it should be noted that although the project scope was limited by the sponsor to water emissions, a broader-scope project could be developed by considering air emissions as well.
CONCLUDING REMARKS

This course was an invaluable experience for both the students and the faculty. It provided the students with an opportunity to do something that is rare in graduate education, but common in industrial practice—the opportunity to work in teams on the solution of a real problem from the basics to virtually its implementation. The students who took this course are involved in doctoral research in extremely diverse areas, from catalysis to biochemical engineering to separations. Thus, each student brought particular skills to the completion of the project. Through the team’s efforts, each student learned to treat real problems from a global perspective within defined constraints. One of the main lessons was that optimum solutions to environmental problems often come from an intelligent reengineering of the process itself, rather than through the adoption of off-the-shelf approaches.

The course was geared for doctoral candidates and most of the students were at an advanced level. Although a different version of such a course could be developed for all graduate students, the time commitment required for a successful interaction with industry could be difficult to meet by beginning graduate students who are engaged in other coursework.

A key to the success of this course was the commitment of the sponsor to the effort. The company sponsor shared valuable data and experience with the students and provided guidance at a level that the faculty alone could not have provided. Likewise, external experts who participated both in the conception and in the offering of this course provided a different and unique perspective that added tremendous value to the educational experience.

Finally, there was a “real” value in return to the company sponsor. Aside from the direct technical contributions, company personnel were exposed to a way of thinking about chemical processes that is different from traditional, unit-operations-based approaches. Essential to this success was the sense of trust and respect that developed among the participants through frequent interactions at different levels.

This course provided several opportunities for the development of instructional modules for use in our undergraduate design class. One of the modules is focused on legal and regulatory aspects, with emphasis on pollution prevention. The other is a design project based on the data obtained by the graduate students and their proposals for the solution of the copper emission problem. The latter was offered as a senior undergraduate design project. The undergraduates who took the project enjoyed working on a real problem using data developed “in house” as the basis for their design calculations and learned a great deal by working within the constraints of an actual industrial situation. A version of this project including technical specifications and economic data is available upon request.

ACKNOWLEDGMENTS

Development of this course was supported by a grant from the Academic Enhancement Program of the University of Virginia. We are indebted to Stan Sitnik of AlliedSignal, Inc., and to Wayne Halbleib of Mays & Valentine for their participation in the course. Support from the National Science Foundation Graduate Research Traineeship program is also gratefully acknowledged.

REFERENCES

One activity that serves to nurture learning and to instill pride and a sense of community within our engineering profession is introducing students to the authors of their textbooks, and at two of the recent AIChE national meetings, Phil Wankat and Don Woods organized a session to do just that. In the session, featured authors were invited to present the "inside story" about their textbook, and then students were given a chance to mingle and to seek autographs and photographs. Other authors who were present in the audience were also introduced, and they too became focal points for the students.

At the Chicago meeting, the featured authors were Christie Geankopolis, author of *Transport Processes and Unit Operations*, and Ron Rousseau, coauthor with Rich Felder of *Elementary Principles of Chemical Processes*. Other authors who were present and were introduced to the students included Klaus Timmerhaus, coauthor with Max Peters of *Plant Design and Economics for Chemical Engineers* and Scott Fogler, author of *Elements of Chemical Reaction Engineering*.

The photographs do not do justice to the enthusiasm generated in the session.

---

*Students are clustered around authors (left to right) Klaus Timmerhaus, Christie Geankopolis, Ron Rousseau, Phil Wankat, and Scott Fogler.* (Photo by courtesy of Daphne Robertson.)

*Photos below: One student's lucky day times three. Barrett Steele poses with (left to right) Ron Rousseau, Klaus Timmerhaus, and Christie Geankopolis.* (Photos by courtesy of Barrett Steele.)
**book review**

**ENVIRONMENTAL CHEMODYNAMICS:**
by Louis J. Thibodeaux
Published by John Wiley & Sons, New York, NY; 593 pages, $69.95 (1996)

**Reviewed by**
T. R. Marrero
University of Missouri-Columbia

Quality, quality! The Second Edition of *Environmental Chemodynamics* is a revised and updated version of the 1979 edition that is an outstanding contribution to chemical engineering textbooks for senior and graduate students. Because of its logical organization, completeness, and extensive index (23 pages), it is quite useful to the practicing engineer who has to review the concepts and calculation techniques of chemical equilibrium and transport processes relevant to the fate and rate of movement of chemicals across air-water, water-soil, soil-air interfaces.

This second edition has many figures (146) and tables (86) with useful illustrations of basic engineering principles and environmental data, plus 34 examples. Each chapter has many references, a majority from primary sources; a total of 369 references are cited. It includes 161 problems (50% more than the first edition), and most of them are practical. A solutions manual is available.

In two chapters, *Environmental Chemodynamics* presents clear and succinct descriptions of chemical engineering principles pertinent to the movement of chemicals in the environment. Three chapters describe the concepts, quantification techniques, and reliability of predictions for the interphase movement of chemicals. One chapter covers the basics of intraphase (air, water, and subterranean media) mass transfer.

The purpose of *Environmental Chemodynamics* is to teach, at a university level, the chemical engineering equilibrium and transport (heat, mass, and momentum) methods applicable to situations involving the movement of chemicals in the natural environment.

The author, Louis Thibodeaux, is the Jesse Coates Professor of Chemical Engineering at Louisiana State University. He is nationally and internationally known for his outstanding research and teaching in the area of environmental science and engineering. His activities in this area have spanned for more than twenty-five years.

A student must first become familiar with the systemic and mnemonic notation used in the text. This neat information is presented in chapter one and allows the specification of controlling factors for different environmental systems. Chapter one includes the definition of “trace” constituents that are important to environmental analyses and a classic example of mass transfer, the re-aeration of natural streams. This example is almost essential for chemical engineering students who have never considered quantitative problems outside of chemical process systems. The reader of chapter one also learns that the law of conservation of mass was first experimentally established by Antoine Lavoisier in 1777.

Chemical engineering basic principles of thermodynamics and transport phenomena are well covered in chapters two and three, respectively. These two chapters teach fundamentals required for the problems presented in the four subsequent chapters. Topics include chemical and thermal equilibrium at environmental interfaces, diffusion, mass transfer, and turbulence. The understanding of these concepts and phenomena for the prediction of chemical movement in the environment is essential to the environmental engineer and complements earlier classroom studies by chemical engineering students. Fundamentals are clearly explained in this book.

The final four chapters are the “meat” of *Environmental Chemodynamics*. The major topics are: Chemical Exchange Between Air and Water (Chapter 4); Chemical Exchange Between Water and Adjoining Earthen Material (Chapter 5); Chemical Exchange Between Air and Soil (Chapter 6); and Intraphase Chemical Transport and Fate (Chapter 7).

Each major topic is divided into subtopics that define the applicable terms, illustrate the concepts and systems, and provide examples and problems from actual events and research studies. The text is not esoteric. Figures illustrate the concepts and explicitly specify the systems of interest. Data in table form are immediately available to the students; these environmental data are not readily found in other chemical engineering textbooks or handbooks. Chapter four well explains a method to calculate the desorption (absorption) of gases from aerated basins and rivers. Chapter five emphasizes the determination of chemical movement at the bottom of quiescent water bodies (ponds, lakes) and flowing streams. Chapter six divides the chemical movement across the air-soil interface into two regions: through the lower layer of the atmosphere and through the upper layer of earthen material. The last chapter presents mathematical models for chemical movement in surface water and well-known methods of mass transport in the lower atmosphere.

In conclusion, this reviewer’s opinion is that *Environmental Chemodynamics* is an excellent resource for practicing engineers as well as the best textbook available for the teaching the fate and transport of chemicals in the environment. The editors of the Wiley-Interscience Series in Environmental Science and Technology are to be commended for including this text in their series on Environmental Science and Technology. ☐
class and home problems

The object of this column is to enhance our readers' collections 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 and which elucidate difficult concepts. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu) or Mark A. Burns (e-mail: maburns@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

START-UP OF A NON-ISOTHERMAL CSTR
Mathematical Modeling

AZIZ M. ABU-KHALAF
King Saud University • Riyadh 11421, Saudi Arabia

One important feature of the CSTR is its operation under steady-state conditions. It shows, however, transient behavior during start-up and shut-down periods of operation, although these periods are relatively short compared to those in steady-state operation. Modeling of these transient periods can be of great value since, during their operation, they affect product quality. Care must be given to the operating conditions involved and the procedures followed in start-up and shut-down.

PROBLEM
Consider a CSTR with an overflow outlet. Solutions of reactants A and B, of equimolar concentrations and at the same feed temperature, are fed at equal flow rates into the reactor. The order of the reaction is known, and the rate constant is a function of temperature. The following are three possible approaches for starting up the reactor:

I • Add both reactants simultaneously into the empty reactor.
II • Start with a certain volume of reactant A, then add both reactants simultaneously.
III • Fill the reactor with A, then add both reactants simultaneously.

Our objective is to model these different types of start-up mathematically under non-isothermal conditions and to develop differential equations (on the basis of material and energy balances) that describe the dynamics of this CSTR, and then solve them numerically.

Note that in start-up methods I and II, the reactor passes through three stages: it fills up, it approaches steady state, and then it operates steadily. In type III, the reactor passes through only the last two states, because it is already full.

Assumptions
1. Negligible variations of heat capacity and heat of reaction with temperature
2. Negligible non-idealities of solutions (which are dilute)
3. No change in volume due to mixing or reaction
4. Constant density
5. No side reactions
6. Since we have a liquid mixture under atmospheric pressure, we can safely equate the internal energy to the enthalpy of the system.
7. Resistance to heat transfer inside the reactor and through its walls, and the shaft work due to mixing, are negligible.

Aziz M. Abu-Khalaf is a member of the chemical engineering teaching staff at King Saud University. His main interests are in mathematical modeling, corrosion, and controlled-release systems.
Start-Up: Type I

During Stage 1 of this start-up type, the reactor is filling up with no output, while the reaction still occurs. Concentration, volume, and temperature are all changing with time. In Stage 2, the reactor overflows (reacting volume becomes constant), but concentration and temperature will change until Stage 3 is reached, in which steady state prevails.

Stage 1.

A mass balance on component \( i \) gives
\[
\frac{d}{dt}(VC_i) = FC_{if} + V\sigma_{ir}
\]
The volume is a variable, so a total mass balance is needed, giving (consider assumption 5)
\[
\frac{dV}{dt} = F \tag{2a}
\]
and, since the reactor is initially empty,
\[
V = Ft \tag{2b}
\]

By expanding the left-hand side of Eq. (1) and using Eqs. (2a) and (2b), we obtain
\[
\frac{dC_i}{dt} = \frac{C_{if} - C_i}{\tau} + \sigma_{ir} \tag{3}
\]
which is subject to the initial condition that as \( t \to 0^+ \), \( C_i = C_{if} \).

An energy balance gives (consider assumptions 2 and 6)
\[
\frac{d}{dt} \left( \sum C_i \hat{H}_i \right) = F \sum C_{if} \hat{H}_{if} - Q^* \tag{4}
\]
in which \( \Sigma \) sums all the components involved. After some manipulations and using Eqs. (1), (2a), and (2b), Eq. (4) becomes
\[
\sum C_i \frac{d\hat{H}_i}{dt} = \frac{1}{\tau} \sum C_{if} \left( \hat{H}_{if} - \hat{H}_i \right) - \sigma_{ir} \sum \sigma_i \hat{H}_i - \frac{Q^*}{Ft} \tag{5}
\]
in which the second term on the right-hand side is the heat of reaction at the temperature of the system. Choosing the inlet temperature as a reference and considering assumption 1, Eq. (5) becomes
\[
\left( \sum c_{pi} C_i \right) \frac{dT}{dt} = -\left( \sum c_{pi} C_{if} \right) \frac{(T - T_i)}{\tau} - \sigma_{ir} \Delta H_i^0 - \frac{Q^*}{Ft} \tag{6}
\]
in which \( \Delta H_i^0 \) is the standard heat of reaction. The heat loss term, \( Q^* \), is related to the surface area of the system, \( S \), and the temperature difference as follows:
\[
Q^* = Sh_{air}(T - T_{amb}) = \frac{4Ft}{D} h_{air}(T - T_{amb}) \tag{7}
\]
After substituting Eq. (7), Eq. (6) becomes
\[
\left( \sum c_{pi} C_i \right) \frac{dT}{dt} = -\left( \sum c_{pi} C_{if} \right) \frac{(T - T_i)}{\tau} - \sigma_{ir} \Delta H_i^0 - \frac{4h_{air}(T - T_{amb})}{D} \tag{8}
\]
subject to the condition that as \( t \to 0^+ \), \( T = T_i \).

Stage 2.

A mass balance gives
\[
\frac{dC_i}{dt} = FC_{if} - FC_i + V\sigma_{ir} \tag{9}
\]
where \( \tau = t - \theta \) and \( \theta = V/F \). Thus, the zero time for this stage is at \( t = 0 \). An energy balance gives the following equation (considering assumption 7):
\[
\frac{d}{dt} \left[ \sum C_i \hat{H}_i \right] = F \sum C_{if} \hat{H}_{if} - F \sum C_i \hat{H}_i - Q^* \tag{10}
\]
By expanding the left-hand side of Eq. (10), substituting Eq. (7) and Eq. (9) and using the definition of the heat of reaction and noting assumption 1, we get, after taking as a reference the inlet temperature,
\[
\left( \sum c_{pi} C_i \right) \frac{dT}{dt} = -\sum c_{pi} C_{if} \frac{(T - T_i) - \tau \Delta H_i^0}{\tau} - \frac{4h_{air}(T - T_{amb})}{D} \tag{11}
\]
subject to the condition that at \( \tau = 0, T = T_i \), where \( T_i \) is the temperature at the end of stage 1.

Stage 3.

Here, modeling can be approached via direct mass and energy balances or by simplifying Eqs. (9) and (11), where the differential terms vanish. In either case, we have
\[
C_{is} = C_{if} + 6\sigma_{ir} \tag{12}
\]
\[
\frac{1}{\theta} \left( \sum c_{pi} C_{if} \right) \frac{(T - T_i) - \tau \Delta H_i^0}{\tau} - \frac{4h_{air}(T - T_{amb})}{D} = 0 \tag{13}
\]

Start-Up Type II

Stage 1.

The system again passes through three stages, as in Type I, but we start with a known volume \( V_i \) of one of the reactants. The governing equations of Stage 1 of this start-up type are
\[
V = Ft + V_i \tag{14}
\]
\[
\frac{dC_i}{dt} = \frac{C_{if} - C_i}{\tau} + \sigma_{ir} \tag{15}
\]
with the condition that at \( t = 0, C_i = C_{i0} \), and
\[
\left( \sum c_{pi} C_i \right) \frac{dT}{dt} = -\sum c_{pi} C_{if} \frac{(T - T_i)}{\tau} - \sigma_{ir} \Delta H_i^0 - \frac{4h_{air}(T - T_{amb})}{D} \tag{16}
\]
with the condition that \( T = T_0 \) at \( t = 0 \).

Stage 2.

Here, we have the same equations as in Stage 2 of Type I (that is, Eqs. 9 and 11), with the difference that \( \tau = t - \theta_i \), where \( \theta_i = (V - V_i)/F \).

Stage 3.

Equations (12) and (13) of Stage 3 in Type I also apply to Stage 3 of Type II.

Start-Up Type III

Since the reactor is initially full, it now passes through only two stages, \( i.e., \) there is no filling-up stage. Again, Eqs. (9) and (11) apply to Stage 1 of Type III, with the initial conditions that at \( t = 0, C = C_{i0}, \) and that \( T = T_0 \). For Stage 2, Eqs. (12) and (13) are applicable.
NUMERICAL SOLUTIONS

Due to the coupling between temperature and concentration, we need to solve the models simultaneously using numerical techniques. In order to start the numerical solution of Eqs. (3) and (8), we must take the limit of these equations as \( t \) approaches zero, giving, for Eq. (3),

\[
\frac{dC_i}{dt} \bigg|_{t=0} = \frac{1}{2} \sigma_i f_0
\]

while for Eq. (8),

\[
\frac{dT}{dt} \bigg|_{t=0} = -\frac{f_0 \Delta H_r^0}{2 \sum c_p C_i(0)}
\]

Since our system is dilute, integration problems will not be serious, and any suitable package that handles initial-value problems can be used (e.g., IVPRK from IMSL). The models of start-up Type I are very stiff and numerical integration will proceed well as long as the system is dilute; otherwise, special techniques or subroutines must be used. Stiff ordinary differential equations are characterized by having widely separated eigenvalues, and special attention to the stability of the numerical technique is required.

Steady-state models are algebraic in nature and have to be solved simultaneously. The package NEQNF from IMSL was used here to solve these models.

Our numerical illustration is based on a second-order reaction between sodium hydroxide (A) and ethyl acetate (B) solutions. The products are ethyl alcohol and sodium acetate. All stoichiometric coefficients are 1 or -1. The rate of reaction is given as \( r = kC_A C_B \), and the rate constant as \( k = 10^{0.31} \exp(-48.32/RT) \), where \( T \) is in K and \( R \) is the gas constant. Other conditions are: \( C_{f0} = 0.1 \) M for reactants and zero for products, and the same for initial concentrations; \( F = 0.5 \) l/min; \( T_F = 24 \) °C; \( T_{amb} = 29 \) °C; \( V = 2.8 \) l; \( V_1 = 1.5 \) l; \( h_{pc} = 2.5 \) J/m²°C min; and \( \Delta H_r^0 = -1.5 \) kJ/mol. The heat capacities for the reactants are 75.25 and 175.3, and for the products are 78.2 and 103.8 J/mol °C. The reactor is cylindrical with a diameter of 15 cm.

DISCUSSION

Three methods of start-up were considered (I, II, and III), with corresponding concentration profiles shown in Figures 1, 2, and 3, respectively. Each component of this system has a stoichiometric coefficient of 1 or -1, and the feed streams do not contain any product. During Type I, the rate of reaction terms takes the form \( r = kC_A^2 \), since both reactants A and B are of equimolar concentrations. Hence, the profiles in Figure 1 are denoted by products and reactants without reference to any specific component. For other types, the form of the reaction rate is \( r = kC_A C_B \), since the concentration of B in these types is initially zero, and the reactor is initially loaded with A. Component B has a concentration profile that is different from A, as shown in Figures 2 and 3.

Comparison of Figures 1 to 4 shows that the performance of Type II lies somewhere between Types I and III, which can also be seen by considering Eqs. (15) and (16). In the limit as \( V_1 \) goes to zero, these equations reduce to Eqs. (3) and (8), respectively, and in the limit as \( V_1 \) goes to infinity (e.g., approaches the total volume of the reactor), these equations reduce, respectively, to Eqs. (9) and (11). Note also the start-up
Type III has the shortest path to steady state and that at any given time the concentration of any reactant or product in this type is less than the concentration of the corresponding component in other types.

It is interesting to consider in Figures 1, 2, and 3 the point of intersection between a reactant concentration profile and a product concentration profile, where they have equal concentrations—beyond this point the product concentration exceeds that of a reactant. For A, this point has the same value of concentration in all start-up types, but occurs at different times. For Type I it occurs at a time less than the time constant of the reactor, while for others its time is larger than the time constant of the system. Thus, Type III is preferable to the others.

Figure 4 shows that the overall temperature rise is not great, because the presence of an inert solvent moderates the temperature effects that would arise from thermal activity. This will hold true even with more highly exothermic reactions in the presence of diluents or a vast excess of one reactant.[1] Figure 4 also shows that the approach to steady state is faster in the case of Type III than in the others. In Type III the reactor is initially full, while in Types I and II there will be an abrupt change at the moment the output stream starts to flow, as seen for Types I and II. At any given time, the temperature of the reacting system is lower in Type III than in others, and this also supports the choice of Type III.

Models of Type I need special attention during numerical integration, specifically at zero time, in order to be able to start the numerical solution. Such attention is not needed in the other two types. Also, if we use concentrated solutions, serious problems may arise during numerical integration that will affect the stability of the method unless special techniques or packages are used. We do not need this in the other types.

In Type I we might face experimental inconveniences, particularly in measurements using conductivity meters, due to lack of material. Air bubbles and violence of mixing at the beginning will affect the results; these effects might not present a serious difficulty in the other types.

Questions for Consideration

1. Under what conditions can we apply Eq. (8) to start-up Type II? Hint: compare Eq. (8) with Eq. (16).

2. Derive Eqs. (17) and (18).

3. Explain, with the help of the model equations and the nature of each start-up type, the above observations.

ACKNOWLEDGMENT

Thanks to Professor M.A. Soliman, J.O Wilkes, and the reviewers of this article for their valuable contributions.

NOMENCLATURE

- \( C_i \): Concentration of component \( i \) (reactant or product), mol/1
- \( C_{i,f} \): Feed concentration of component \( i \), mol/1
- \( C_{i,0} \): Initial concentration of component \( i \), mol/1
- \( C_{i,ss} \): Steady-state concentration of component \( i \), mol/1
- \( c_p \): Heat capacity of component \( i \), kJ/mol °C
- \( D \): Diameter of the reactor, m
- \( F \): Total flow rate, 1/min
- \( h_{air} \): Heat transfer coefficient for air, kJ/m² °C min
- \( H_i \): Enthalpy of pure component \( i \) inside and at outlet, kJ/mol
- \( H_{i,if} \): Enthalpy of pure component \( i \) in the feed, kJ/mol
- \( k \): Reaction rate constant, 1/mol min
- \( Q' \): Rate of heat loss to the surroundings, kJ/min
- \( R \): Gas constant, 0.008314 kJ/mol K
- \( S \): Surface area of the reactor, m²
- \( T \): Temperature of the system and outlet, °C
- \( T_{amb} \): Temperature of the surroundings, °C
- \( T_i \): Feed temperature, °C
- \( T_{ss} \): Steady-state temperature, °C
- \( t \): Time, min
- \( V \): Volume of the reacting system, l
- \( V_i \): Starting volume of start-up Type II, l
- \( \theta \): Time constant of the reactor, min
- \( \theta_i \): Time constant for Type II, min
- \( \Delta H^0_i \): Standard heat of reaction, kJ/mol
- \( \sigma_i \): Stoichiometric coefficient, positive/negative for products/reactants
- \( \tau \): Time for Stage 2, min

REFERENCES

HELPING STUDENTS BECOME BETTER MATHEMATICAL MODELERS
Pseudosteady-State Approximations

ANNETTE L. BUNGE, RONALD L. MILLER
Colorado School of Mines • Golden, CO 80401

Undergraduate and graduate students completing their first course in applied engineering mathematics or transport phenomena are often confused about several aspects of modeling physical systems. These may include clearly stating and understanding simplifying assumptions, advantages and limitations of various solution strategies, ways to quickly check that derived solutions seem reasonable using limiting cases, determination of applicable ranges of approximate solutions, how to use limiting cases obtained from exact solutions, and physical interpretation of mathematical results. We have developed a pedagogically sound approach to addressing these issues using a single physical transport problem that can be analyzed with multiple mathematical models. The objective of this paper is to present the problem with two pseudosteady-state solutions and to provide several examples of study questions we pose to students to help them better understand and interpret the results of each solution.

The problem involves mass transfer from topical formulations (ointments or creams applied to skin) containing drugs in suspension. A moving boundary develops in this system and mathematical representations are amenable to pseudosteady-state, similarity transform, and regular perturbation solutions. In this paper we formulate the descriptive differential material balance model and obtain two different pseudosteady-state solutions. We will also present and discuss several study questions to assign students based on results of each model solution (presented in italics).

PROBLEM DESCRIPTION

Delivery of drugs to skin is important for treatment of a number of skin diseases. Many topically applied drugs are solid suspensions in a vehicle consisting of an ointment or cream base. That is, the total amount of active ingredient exceeds the solubility limit of the formulation. In these systems, the solid drug dissolves into the vehicle, diffuses through the vehicle to the skin, establishes local phase equilibrium with the outer layer of skin, diffuses through the skin, and finally is swept away by internal circulation. In many cases, skin represents the rate limiting barrier for mass transfer. Occasionally, particularly for highly insoluble suspension-type formulations or for applications on damaged skin, the primary mass transfer resistance will be the vehicle itself.

Release rates from topical formulations are experimentally measured by spreading the drug suspension on a permeable membrane and then monitoring the appearance of drug in an initially drug-free solution on the opposite side of the membrane, the receiving chamber, as shown in Figure 1. The receiving chamber volume is generally large enough so that drug accumulation can be neglected. Mass transfer resistances in the membrane are usually much smaller than in the formulations, and the system can be treated as if the membrane was not present. Consequently the concentration in contact with the membrane is approximately the same as the concentration of the receiving chamber (i.e., $C = 0$).

If the drug is finely divided, uniformly suspended, and rapidly dissolves, then two zones will develop as illustrated schematically in Figure 2. Far from the receiving chamber ($0 \leq x \leq L$), the drug will be present as a solid suspension at the original starting concentration $C_0$. In the region adjacent to the receiving chamber ($0 \leq x \leq \delta$), all of the solid will have dissolved and the drug will be present in concentrations below the solubility limit, $C_s$, as described by Fick's law.[1]
That is,

\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad \text{for} \quad 0 \leq x \leq \delta
\]  

(1)

where

\[
C = 0 \quad \text{at} \quad x = 0 \quad \text{for} \quad t \geq 0
\]

(2)

\[
C = C_s \quad \text{at} \quad x = \delta \quad \text{for} \quad t < 0
\]

(3)

The location of the sharp boundary between the fully dissolved and suspended drug zones (\(\delta\)) will advance in time as required to satisfy the drug material balance at \(x=\delta(t)\):

\[
(C_0 - C_s) \frac{\partial \delta}{\partial t} = D \frac{\partial C}{\partial x} |_{x=\delta}
\]

(4)

where

\[\delta = 0 \quad \text{at} \quad t = 0\]

(5)

It is convenient to nondimensionalize the differential equations and restricting conditions using the following definitions:

\[
\theta = \frac{C}{C_s}, \quad \eta = \frac{x}{L}, \quad \chi = \frac{\delta}{L}
\]

(6)

where \(\delta = 0\) at \(t = 0\).

\[
\theta = 0 \quad \text{at} \quad \eta = 0 \quad \text{for} \quad \tau \geq 0
\]

(9)

\[
\theta = 1 \quad \text{at} \quad \eta = \chi \quad \text{for} \quad \tau > 0
\]

(10)

\[
\chi = 0 \quad \text{at} \quad \tau = 0
\]

(11)

The concentration profile of drug in the formulation can then be determined by solving two coupled differential equations, Eq. (7) and Eq. (8), for three conditions, Eqs. (9) through (11).

The concentration profile is only occasionally of interest. Practically, it is usually more important to determine quantities such as the mass of drug released as a function of time, the time required for all of the drug to dissolve, and the fraction of the drug that is released when dissolution is complete.

The amount of drug released from the vehicle at \(\eta = 0\) per unit of exposed area over a period of time from zero to \(t\) is determined by integrating the mass flux at the vehicle receiving chamber interface over time. That is,

\[
M_R = A \int_0^t \frac{\partial C}{\partial x} \mid_{x=0} \cdot \text{dt}' = ALC_s \left[1 - C_s \right] \int_0^\gamma \theta \mid_{\eta=0} \cdot \text{d}\tau'
\]

(12)

where \(\tau'\) and \(\tau'\) are dummy variables of integration. The time required for all of the solid drug to dissolve (\(\tau_f\)) is the time at which \(\chi = 1\), and the mass fraction released when all of the drug dissolves is specified by Eq. (12) when \(\tau = \tau_f\).

**PSEUDOSTEADY-STATE APPROXIMATION**

When \(C_s\) is much larger than the drug solubility \(C_s\), the dissolution boundary \(\delta\) moves slowly relative to diffusion in the dissolved zone. It is then appropriate to assume that the concentration profile in the dissolved zone (\(0 \leq \eta \leq \chi\)) is approximately at steady state. That is,

\[
\frac{\partial^2 \theta}{\partial \eta^2} = 0 \quad \text{for} \quad 0 \leq \eta \leq \chi
\]

(13)

which is solved along with the conditions listed in Eqs. (9) and (10) to give

\[
\theta = \frac{\eta}{\chi}
\]

(14)

where the movement of \(\chi\) in time is determined by substituting for \(\theta\) in Eq. (8).
\[
\frac{d\chi}{dt} = \frac{\partial \theta}{\partial \eta} \bigg|_{\eta=\chi} \frac{1}{\chi} = (15)
\]
which is integrated with Eq. (11) to give
\[
\chi = \sqrt{2\tau}
\]
Thus, the concentration profile of the drug in the formulation is approximately represented by
\[
\theta = \frac{\eta}{\sqrt{2\tau}} = (17)
\]
provided that \( C_s < C_o \) (i.e., \( R << 1 \)), guaranteeing that the pseudosteady-state assumption is valid.

The amount of drug released from the vehicle at \( \eta = 0 \) per unit of exposed area over a period of time from zero to \( \tau \) is
\[
M_R = ALC_o(1-R) \int_0^\tau \frac{1}{\sqrt{2\tau}} d\tau = (18)
\]
\[
M_R = ALC_o(1-R)/\sqrt{2\tau} = (19)
\]
The time required for all of the solid drug to dissolve (\( \tau_f \)) is 1/2, during which the mass fraction released is
\[
\frac{M_{Rf}}{M_o} = \frac{M_R}{ALC_o} = 1 - R
\]
According to Eq. (20), the fraction of the original drug mass remaining in the formulation is \( R \). Thus, according to the pseudosteady-state solution, the average concentration in the formulation when all of the drug has dissolved is \( C_o \), which is not correct. If the concentration profile in the dissolved regions varies linearly from \( C_o \) to zero, the average concentration when all the drug is dissolved should be \( C_o/2 \).

**HIGUCHI APPROXIMATION**

More than thirty years ago, Higuchi\(^2\) used a variation of the pseudosteady-state solution to obtain a different result. Like the solution just described, Higuchi assumed that the concentration profile had reached its steady-state value rapidly relative to the movement of the dissolution front (i.e., \( \theta = \eta/\chi \)). He chose, however, to determine the location of the dissolution boundary by requiring that the mass of drug that has left the formulation
\[
\frac{M_R}{A} = \int_0^L Cdx = L(C_o - \int_0^L \frac{C_o}{dx} = = \int_0^L C_0 dx = \delta - \int_0^L Cdx)
\]
be equal to the amount that has diffused across the boundary at \( x = 0 \) into the receptor
\[
\frac{dM_{Rf}}{dt} = AD \bigg| \frac{\partial C}{\partial x} \bigg|_{x=0}
\]
Written in dimensionless form, Eqs. (21) and (22) become
\[
\frac{dR}{dt} = \int_0^\infty \frac{\partial \theta}{\partial \eta} \bigg|_{\eta=\chi} \frac{1}{\chi} = (23)
\]
Integrating Eq. (23), we obtain
\[
M_R = ALC_o(1-R/2)/\chi
\]
which can be then differentiated
\[
\frac{dM_R}{dt} = ALC_o(1-R/2) \frac{\partial \delta}{\partial \eta} = (24)
\]
and combined with Eq. (24) to yield
\[
\frac{d\chi}{dt} = \frac{1-R}{1-R/2} \frac{\partial \eta}{\partial \eta} \bigg|_{\eta=x} = \frac{1-R}{1-R/2} \chi
\]
Finally, Eq. (27) is integrated with the restriction that \( \chi = 0 \) at \( \tau = 0 \) to give
\[
\chi = \frac{\sqrt{2(1-R)}}{1-R/2}
\]
Substituting Eq. (28) into Eq. (25), we obtain an expression for the cumulative mass released,
\[
M_R = ALC_o \sqrt{2(1-R)(1-R/2)} \tau = ALC_o \sqrt{2(1-R/2)} \tau/\epsilon
\]
which is slightly different than the pseudosteady-state result given in Eq. (19). The dimensionless time required to completely dissolve the drug is
\[
\tau_f = \frac{1-R/2}{2(1-R)}
\]
at which time the mass fraction released would be
\[
\frac{M_{Rf}}{M_o} = \frac{M_R}{ALC_o} = 1 - R/2
\]
According to Eq. (31), the fraction of the original drug mass remaining in the formulation is \( 1 - (1-R/2) = R/2 \). Thus, the Higuchi solution correctly predicts that the average concentration in the formulation when all of the drug has dissolved is \( C_o/2 \). Table 1 summarizes and compares expressions for the pseudosteady-state and Higuchi solutions, respectively.

**COMPARING PSEUDOSTEADY-STATE AND HIGUCHI SOLUTIONS**

Which of the two pseudosteady-state solutions is likely to be more correct (i.e., more closely match the exact solution) when \( R \) is no longer very small?

Based on mass balance, the Higuchi solution is superior. The Higuchi solution required that the mass of drug released into the receptor and the mass remaining in the formulation must always equal the total mass of drug in the original formulation. A similar requirement was not made in the standard pseudosteady-state solution. Most notably, at the moment that all of the drug has completely dissolved, the
pseudosteady-state solution predicts that the average concentration in the formulation is \( C_v \), which is two times larger than the correct value of \( C/2 \).

**AFTER THE DRUG HAS COMPLETELY DISSOLVED**

What happens after the drug has completely dissolved? Are the two pseudosteady-state solutions valid for all times? If the solution is not always valid, when does its validity expire? What happens then? How would you describe the new situation?

The drug will continue to be released until the concentration reaches zero throughout the formulation. Equations (19) and (29) describing the cumulative mass of drug released only apply while some drug remains undissolved (i.e., as long as \( \tau \leq \tau_f \)). Drug release after dissolution is complete is described by the solution of the unsteady-state diffusion equation (e.g., by separation of variables) with an initial concentration profile equal to the concentration profile in the dissolved region when \( \eta = 1 \) (i.e., \( \theta = \eta \) at \( \tau > \tau_f \)) and no flux at \( \eta = 1 \). When \( \tau > \tau_f \),

\[
\theta = 2 \sum_{m=0}^{\infty} \frac{(-1)^m}{\lambda_m^2} \sin(\lambda_m \eta) e^{-\lambda_m^2 (\tau-\tau_f)/\varepsilon} \quad (32)
\]

\[
\frac{M_R}{\text{ALC}_o} = \frac{M_{\text{RF}}}{\text{ALC}_o} + 2R \sum_{m=0}^{\infty} \frac{(-1)^m}{\lambda_m^2} \left( 1 - e^{-\lambda_m^2 (\tau-\tau_f)/\varepsilon} \right) \quad (33)
\]

where \( \lambda_m = (2m+1)\pi/2 \).

An interesting exercise is to ask students to show that \( (M_R - M_{\text{RF}})/(\text{ALC}_o) = R/2 \) in the limit of large \( \tau \). Thus, in the limit of large \( \tau \), the Higuchi solution correctly predicts \( M_R/(\text{ALC}_o) = 1 - R/2 + R/2 = 1 \), while the pseudosteady-state solution predicts incorrectly that \( M_R/(\text{ALC}_o) = 1 - R + R/2 = 1 - R/2 \neq 1 \). We note that for small values of \( R \), the solubility limit is very low, and consequently little drug will remain in the formulation once the drug has dissolved. That is, for small values of \( R \), \( 1 - R/2 \approx 1 \).

**WHEN THE SOLUBILITY LIMIT OF THE DRUG IS NOT EXCEEDED**

What if the drug concentration in the topical formulation is less than its solubility limit (i.e., \( C_0 < C_s \))? How will the cumulative release rate from the formulation compare with the case when suspended drug is present? For the same drug concentration, will a dissolved or suspended drug give a higher release rate?

An interesting exercise is to compare the release rate from topical formulations containing suspended drug with the rate from formulations containing only dissolved drug. When the drug is entirely dissolved in the formulation, drug release will be described by the solution of the unsteady-state diffusion equation, Eq. (7), with an initial concentration of \( C_0 \) throughout the formulation (i.e., \( \theta = 1/R \) at \( \tau = 0 \) for \( 0 \leq \eta \leq 1 \)) and no flux at \( \eta = 1 \). This is easily solved by separation of variables to obtain

\[
\theta = 2 \sum_{m=0}^{\infty} \frac{1}{\lambda_m} \sin(\lambda_m \eta) e^{-\lambda_m^2 \tau/\varepsilon} \quad (34)
\]

\[
\frac{M_R}{\text{ALC}_o} = 2 \sum_{m=0}^{\infty} \frac{1}{\lambda_m^2} \left( 1 - e^{-\lambda_m^2 \tau/\varepsilon} \right) \quad (35)
\]

where \( \lambda_m = (2m+1)\pi/2 \). Although not obvious from Eq. (35), for short times

\[
\frac{M_R}{\text{ALC}_o} = 2 \sqrt{\frac{\tau/\varepsilon}{\pi}} \approx 2 \sqrt{\frac{\tau(1-R)}{\pi R}} \quad (36)
\]

which is the solution to Eq. (7) (most easily obtained by Laplace transforms) when the formulation is semi-infinite (i.e., \( L \rightarrow \infty \) or when \( \tau \) is short enough that the concentration profile has not penetrated far into the formulation). This is an interesting result, since for both suspended and dissolved drug formulations, the cumulative mass released is proportional to \( \sqrt{\tau/\varepsilon} \) until changes in the concentration profile have penetrated almost across the formulation.

**ADDITIONAL STUDY QUESTIONS AND ILLUSTRATIVE EXERCISES**

In this section, we present additional study questions and exercises that can be assigned. We find that students are usually more proficient at solving a problem than at using the solution they have derived. With the availability of symbolic mathematical tools such as Mathematica or Maple, it is reasonable to ask students to plot and analyze calculations from their solutions. A goal of the questions posed here is to require students to use and think about the physical meaning of their solu-

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary of Equations for Pseudo Steady-State and Higuchi Solutions</strong></td>
</tr>
<tr>
<td><strong>Quantity</strong></td>
</tr>
<tr>
<td>( \theta ) for ( 0 \leq \eta \leq \chi )</td>
</tr>
<tr>
<td>( \theta ) for ( \chi \leq \eta \leq 1 )</td>
</tr>
<tr>
<td>( \chi )</td>
</tr>
<tr>
<td>( M_R/\text{ALC}_o )</td>
</tr>
<tr>
<td>( \tau_f )</td>
</tr>
<tr>
<td>( M_{\text{RF}}/\text{ALC}_o )</td>
</tr>
</tbody>
</table>

---

Fall 1997
tion. These exercises can be used in many different ways. For example, we have assigned a series of solution strategies as a take-home exam that students work on for several weeks, submitting solutions to sections as they learn each new solution method (a just-in-time approach). Alternatively, they can be used as a series of homework or in-class problems illustrating many of the analytical mathematical techniques chemical engineers need for solving partial differential equations (e.g., approximate solutions by pseudosteady-state and regular perturbation, separation of variables, Laplace transforms, and similarity transforms).

Plot the concentration profile as a function of dimensionless position, x/L, in the formulation as predicted by the standard pseudosteady-state and Higuchi solutions at a given time for a specified R. Consider formulations in which the drug is initially fully dissolved (i.e., R > 1) as well as initially a suspended solid (i.e., R < 1).

Figure 3 shows C/C₀ when R = 0.5, 0.8, 1, and 2 at τ/ε is 0.10. This is the appropriate way to plot concentration if R changes as a result of changes in C₀. An alternative plot of C/ C₀ is more suitable when the total amount of drug is held constant and R changes by altering the formulation so that C₀ changes, an analysis that can be tied to questions about determining which formulation will be more efficacious (i.e., more drug is released from the formulation during the same amount of time). This plot is also useful for instructing students about the limitations of approximate solutions. For example, when R = 0.8 (i.e., C₀/C₀ = 1.25), the pseudosteady-state solution predicts a smaller slope (and thus a smaller rate of drug release) than when C₀ is reduced to C₀ (i.e., R = 1). This is physically incorrect and a result of the pseudosteady-state solution being used outside of the appropriate range of R. This same inconsistency is not observed for the Higuchi solution.

Calculate and plot the fraction of the initial drug mass released as a function of √(τ/ε) = √(Dt/ L²) for different values of the solubility ratio, R. Compare predictions from the Higuchi and pseudosteady-state solutions while suspended drug remains and then use Eq. (33) to describe drug release after all of the drug has dissolved.

Figure 4 presents the mass fraction released (i.e., M₉/ (A L C₀)) as a function of √(τ/ε) = √(Dt/ L²) for R = 0.2, 0.5, 0.9, >1 as predicted by the pseudosteady-state (S) and Higuchi (H) solutions while undissolved solid remains. The dashed curves represent the solution when drug is completely dissolved (i.e., Eq. 33 when R < 1 and Eq. 35 when R > 1). Significantly, the pseudosteady-state solution has lost mass as indicated by the fact that the total mass fraction of drug released approaches 1 - R/2 instead of the correct value of 1.

The end point of the solid lines, indicated by either an H or an S, represents the mass fraction of drug released during the time required for all of the drug to dissolve (i.e., τ/ε). When the total amount of drug provided greatly exceeds its solubility limit (i.e., R is small), undissolved drug remains for a long time. But as R approaches one, the drug excess over the solubility limit decreases with a consequent decrease in time for complete dissolution.

How does the cumulative amount of drug release vary with time (does the rate increase, decrease, or stay constant)? Is there a steady state? Consider formulations in which the drug is initially fully dissolved (i.e., R > 1) as well as initially a suspended solid (i.e., R < 1).
As indicated in Eqs. (19) and (30) and illustrated in Figure 4, the mass fraction released is proportional to the square root of time as long as some drug remains as a suspended solid. When the formulation initially contains only dissolved drug, the mass fraction released is still proportional to the square root of time as long as less than about a third of the original mass is released. This problem does not reach steady state (except when all of the drug has left the formulation).

Federal regulations require that labels indicate the concentration of active ingredient in a topical formulation. If the concentration of a suspended active ingredient is the same, but the solubility in two formulations is different, which formulation will be more effective (i.e., deliver drug at a higher rate)?

The answer to this question is provided in Figure 4, which illustrates the case when the total amount of drug remains constant but the formulation is altered to increase the solubility limit \( C_s \). The formulation with the higher solubility should deliver drug more rapidly. Increasing the solubility limit (increasing \( R \)) increases the amount of dissolved drug available for diffusion across the formulation. The Higuchi solution predicts this expected result (i.e., that increasing \( R \) should increase the rate of drug release into the receptor solution). By contrast, the pseudosteady-state solution fails when \( R \) approaches 1, incorrectly predicting that the release rate is smaller when \( R = 0.9 \) than for \( R = 0.2 \) or 0.5.

How does increasing the amount of drug affect the cumulative mass released if the solubility limit is fixed? Consider formulations in which the drug is initially fully dissolved (i.e., \( R > 1 \)) as well as initially a suspended solid (i.e., \( R < 1 \)).

If the solubility limit is fixed, increasing the initial drug concentration will cause \( R \) to decrease and will increase the release rate into the receptor solution, as shown in Figure 5. (Again, the pseudosteady-state solution erroneously predicts that decreasing \( R \) from 1 to 0.9 causes the release rate to decrease). If \( R < 1 \), the release rate is limited by the drug's solubility in the vehicle, and increasing the total drug concentration does not proportionally increase the release rate (e.g., compare \( R = 1 \) and 0.5). The pseudosteady-state solution predicts that the rate of release is proportional to \( \sqrt{C_0 - C_s} \); the Higuchi solution predicts the release rate is proportional to \( \sqrt{C_0 - C_s}/2 \).

A FINAL NOTE

In this paper we have used mass transfer from topical drug formulations to illustrate development of two pseudosteady-state solutions and provided several study questions that can be used to help students become better mathematical modelers.

REFERENCES


NOMENCLATURE

- \( A \): Area of vehicle application
- \( C \): Concentration of drug in the vehicle, mass/volume
- \( C_o \): Original concentration of drug in the vehicle, mass/volume
- \( C_s \): Solubility concentration of drug in the vehicle, mass/volume
- \( D \): Effective diffusivity of drug through the vehicle
- \( L \): Thickness of the vehicle
- \( m \): Index on summation, Eqs. (32) - (35)
- \( M_o \): Mass of drug originally present in the formulation, ALC
- \( M_R \): Cumulative mass of drug appearing in the receiving chamber
- \( M_{kr} \): Cumulative mass of drug appearing in the receiving chamber during the time required for all of the drug to dissolve
- \( R \): Ratio of the solubility concentration to the original drug concentration, \( C_s/C_o \)
- \( t \): Time since application of the drug suspension
- \( x \): Axial position in the vehicle

GREEK LETTERS

- \( \delta \): Dissolution front position in the vehicle
- \( \epsilon \): Ratio of \( C_s \) to the difference between \( C_s \) and \( C_o \), Eq. (6)
- \( \eta \): Dimensionless axial position in the vehicle, Eq. (6)
- \( \lambda_m \): Eigenvalue in Eqs. (32)-(35), \( = (2m + 1)\pi/2 \)
- \( \theta \): Dimensionless concentration in the vehicle, Eq. (6)
- \( \tau \): Dimensionless time, Eq. (6)
- \( \tau_f \): Dimensionless time required for all of the drug to dissolve
- \( \chi \): Dimensionless dissolution front position in the vehicle, Eq. (6)

Figure 5. Mass fraction released divided by \( R \) (i.e., \( M_o/(ALC_o) \)) as a function of \( \sqrt{Dt/L^2} \) for \( R \) equal to 0.2, 0.5, 0.9, and 1 as predicted by the pseudosteady-state (S) and Higuchi (H) solutions (while undissolved solid remains) or by the dissolved solid solutions (indicated by dashed curves).
A NOVEL LABORATORY COURSE ON ADVANCED ChE EXPERIMENTS

J. LAUTERBACH, S. WHITE,* Z. LIU, G.M. BODNER,* W.N. DELGASS
Purdue University • West Lafayette, IN 47907

The chemical engineering curriculum in the United States has trained generations of technical experts who have successfully optimized chemical processes and products once they entered the chemical industry. The U.S. chemical industry, however, has entered a critical stage in which it must be able to create new and differentiated value through technical innovations that are essential for long-term survival. This innovation process will require new skills that go far beyond the traditional expertise for the optimization of tasks possessed by young chemical engineers. The innovators must be able to identify new opportunities, explore the boundaries of technology, evaluate critical issues, develop and implement technologies, and communicate effectively with scientists and engineers from other disciplines. Therefore, one of the most important educational tasks of a modern university, in combination with a strong theoretical foundation, is to challenge students in laboratory courses to think, explore, hypothesize, plan, solve, and evaluate.

The typical sequence of laboratory skills development stops short of introducing young engineers to the most critical aspects of experimental work. Chemical engineers usually begin developing their laboratory skills in chemistry courses, where experiments are closely managed. At this early stage in their development, students follow detailed instructions and learn basic principles by observing the results. In the undergraduate engineering laboratory course (the “unit operations lab”), students have more freedom in experimental design but still have well-defined objectives and manipulate equipment someone else has set up.

It is rare, however, for undergraduate students to be taught how to create new experiments. It is also rare for undergraduate students, and hence beginning graduate students, to have an appreciation for the care, planning, design, and testing required to produce equipment that will give reliable and useful results. Even such simple issues as leak testing or adapting analytical devices to new tasks are outside most students’ experience. Even more important is an absence of opportunities to learn how the lessons learned from the failure of an approach can be fed back into the empirical process to seed the finally successful idea. All these skills require more creative freedom than is usually allowed in a well-structured laboratory course. In the novel laboratory teaching approach described here, we try to provide students with a learning environment that allows them to develop advanced experimental skills that are necessary for success in research and development environments.

LABORATORY EQUIPMENT

A true opportunity for students to discover and develop experimental skills is expensive in both hardware and the recurring costs associated with providing the freedom to

---

* Department of Chemistry, Purdue University, West Lafayette IN 47907

---

Jochen Lauterbach is Assistant Professor of Chemical Engineering at Purdue University. He received his Diploma in Physics from the University of Bayreuth, Germany, in 1992 and his PhD in Chemistry from the Free University of Berlin, Germany, in 1994. His research focuses on nonlinear phenomena in heterogeneous catalysis, imaging surface processes in situ with ellipsometry, and the characterization of polymer-metal interfaces using surface second harmonic generation.

Scott R. White is a PhD graduate student in Science Education at Purdue University. He received his BS in Chemistry and Secondary Education Certification in 1992 from Harding University. He received his MS in Chemistry from Purdue University in 1996 with G.M. Bodner. His research interests are in teaching and learning in science and curriculum reform.

Zhufang Liu is a research associate in the School of Chemical Engineering. He is responsible for the Dow Advanced Instrumentation Laboratory and designs and develops new experimental procedures. He received both his BS in Chemical Engineering (1983) and his MS in Polymer Science (1986) from Tianjin University, China, and his PhD in Chemical Engineering from the University of Virginia (1995).

George M. Bodner is Professor of Chemistry and Education at Purdue. He received his BS in Chemistry from the State University of New York, Buffalo (1969) and his PhD in inorganic and organic chemistry from Indiana University (1972). His research interests are teaching theory, overcoming barriers to curriculum reform, and understanding the conditions for appropriate use of technology in teaching and learning chemistry.

W. Nicholas Delgass is Professor and Associate Head of Chemical Engineering at Purdue University. He received his BS degrees in Chemical Engineering and Mathematics at the University of Michigan in 1964 and his MS (1966) and PhD (1969) degrees in Chemical Engineering from Stanford University. His teaching interests are in reaction engineering, catalysis, the chemical process industry, and laboratory. His research is on kinetic and spectroscopic characterization of heterogeneous catalysts. He is the co-editor of the Journal of Catalysis.
make mistakes. This expense is often a strong deterrent to the development of the laboratory content of chemical engineering curricula. We have been fortunate to have the interest and commitment of the Dow Chemical Company in this educational investment in future experimentalists. Dow's financial support has made possible this version of the laboratory and the educational opportunities it affords. We note, however, that the concept of combining the research in chemical engineering at the host institution with the experimental expertise of interested faculty and equipment dedicated to support students is a portable one and can provide a vehicle for exporting this approach to laboratory instruction virtually anywhere. At Purdue, equipment has been chosen to allow us to design projects that involve a variety of experimental techniques in which new apparatus can be created. The projects in the early stage of this course are planned so that future generations of students will benefit from the new instrumentation. They may then, for example, modify the existing equipment for their purposes.

The initial focus of the lab development project has been in adsorption, catalysis, and reaction engineering. Instrumentation available in the teaching laboratory includes

- A Fourier transform infrared spectrometer for molecular identification of adsorbed or gas phase species
- A mass spectrometer for chemical analysis of atmospheric streams from reactors or adsorption systems
- A scanning force microscope for topographical analysis at the nanometer scale
- A surface area and pore structure apparatus for analysis of active porous materials such as catalysts
- An atomic adsorption spectrophotometer for elemental analysis of solids
- A gas-chromatograph for chemical reaction analysis

### TABLE 1
**Lecture Topics**

- How to perform a successful literature search
- Data acquisition and programming of virtual instrumentation
- Vacuum technology
- Flanges and fittings
- Scientific writing
- Scientific oral presentations
- Molecular vibrations
- Vibrational spectroscopy—experimental aspects
- Heterogeneous catalysis—an overview
- Adsorption and desorption
- Thermal desorption spectroscopy
- Scanning probe microscopy

**STUDENT BODY, COURSE STRUCTURE, AND STUDENT EVALUATION**

Experiments for this course were piloted with two separate groups of honors students in 1994 and 1995. In the spring semester of 1997, the course was offered the second time at Purdue. Over twenty students were interested in this novel course approach, but due to space limitations, only twelve could be admitted to the course. The student body was heterogeneous, consisting of three chemical engineering juniors, one chemical engineering senior, one chemistry senior, four chemical engineering graduate students (first and second year), two chemistry graduate students (first and third year), and one materials engineering graduate student (first year). In contrast to the previous years, the undergraduate students were not honors students, but experimentally interested students with various grade point averages.

The students were divided into three groups of four and each group was given an open-ended project. The project descriptions provided the groups with an overall project objective and a well-defined starting point, but required them to develop and pursue their own research ideas. When the groups were organized, care was taken to obtain an equal distribution of students of different levels, departments, and gender for each group, simulating an industrial research environment. For most students, this course was their first experience in a group where graduate and undergraduate level students from different backgrounds had to work together to achieve a common goal. In the beginning, the students had to assign the roles of leader, experimentalist, and analyst among the group members. The diversity of the groups clearly added a learning dimension. The course was also successful with undergraduate chemical engineering students only, however. While those groups were honors students, it is our belief that a genuine interest in the hands-on aspects of chemical engineering is more important than the students' grade point averages.

The total time allotted for the course was two three-hour blocks per week. A combination of approximately 80% laboratory time and 20% lecture time was chosen to give the students enough time to gain hands-on experience with designing, building, and testing effective experimental equipment and adapting modern analytical instrumentation for chemical engineering measurements. A conference room was chosen over a classic classroom setting for lectures and for student presentations to facilitate discussions between the students.

The lectures were concentrated in the first six weeks of the semester (two hours of lecture per week) and covered a variety of topics in instrumentation, molecular-level measurements, and computer data acquisition. The diverse backgrounds of the students required implementation of a teaching philosophy that started with basics and built progressively and at a reasonably fast pace to a deeper and more applied level. Lectures and demonstrations were also given in scientific writing, literature search, and oral-presentation skills. A summary of topics covered in the lectures can be found in Table 1.

There were no quizzes, tests, or final exams for this course. Student evaluation was based on three major factors:
• Performance in the laboratory (motivation, ideas, group dynamics, results)
• Oral presentations (one 15-minute talk for each group member during the semester as well as so-called 5-minute updates every Tuesday morning, showing progress and drawbacks encountered during the last week and encouraging student discussions)
• Written reports (each group wrote a total of three reports about their progress during the semester)

While the evaluation for the first two points was on an individual basis, all group members received the same grade for their reports, motivating them to work closely together. The students were asked to turn in their individual contributions to the papers, not for grading purposes but to help them improve their writing skills and to provide them with individual feedback if necessary.

PROJECTS

One project was given to each of the three student groups. These projects were designed in advance by the instructors around space and instrument-use limitations. Due to the open-ended nature of the projects, it was not possible to plan the whole course in advance—which at a later stage in the semester caused some logistical problems when more than one group wanted to use the same instruments (this problem was solved by offering extra laboratory hours). Due to the open-ended nature of the research projects, it proved to be important to closely monitor students’ progress, without imposing the instructors’ opinion on their approach. Frequent, open discussions with the group were by far the most effective way to guide their research.

Project 1 involved the synthesis and characterization of the mesoporous materials MCM-41 and ZSM5. The students were motivated to study the effects of process variables on the zeolite properties, such as pore size and acidity. Available instrumentation for this project was a physisorption apparatus, atomic absorption, X-ray diffraction, mass spectroscopy, and nuclear magnetic resonance. This project had no major design component and therefore was able to make use of a wider variety of techniques to characterize the chosen materials.

Project 2 involved the design and construction of an IR transmission cell to perform an IR spectroscopy study on supported catalysts. The students built the reaction cell around a 2 3/4-inch Conflat cross, which was provided to them as a starting point. The students then had to design a sample holder with heaters and thermocouples, a simple gas inlet system with flowmeters, and a gas analysis system using the given mass spectrometer setup. After several attempts and many iterations with the instructors, the final design was built by the chemistry machine shop. During this process, the students learned that it is important to pay attention even to minor details, such as the material used for the screws or how to attach CaF₂ windows to a metal flange. The reaction chosen by the instructor was CO oxidation, and the students opted for a SiO₂-supported Pt catalyst, which they prepared and characterized with atomic absorption, scanning electron microscopy, and chemisorption. The C-O stretching vibration of CO adsorbed on the Pt particles was observed during adsorption, desorption, and reaction conditions.

Project 3 will be discussed in detail. It included design and construction of an attenuated total reflection (ATR) IR cell to perform liquid-phase IR measurements. The group was composed of a third-year chemistry graduate student, a first-year chemical engineering graduate student, and two chemical engineering juniors. The objectives of the project were to teach the students how to design and build an optical device from scratch and how to perform IR vibrational spectroscopy.

The students were asked to design and build an ATR cell

Design of ATR Cell and LABVIEW Programming

Keywords:
• Fourier transform infrared spectroscopy
• Attenuated total internal reflectance
• Infrared optics
• IR sampling of liquids
• Virtual instrumentation
• LABVIEW instrument interface programming
• Mass spectroscopy

This project is divided into two separate parts, which in the beginning have to be performed simultaneously. First of all, we are interested in the control of the quality of liquids. For that purpose, we want to use Fourier transform IR vibrational spectroscopy to obtain vibrational spectra of liquids. We will use attenuated total internal reflectance spectroscopy (ATR), a powerful and versatile tool for IR liquid sampling. The group has to design and realize a small ATR cell including the IR optics, which will fit into the sample compartment of the FTIR spectrometer available in the Dow lab. Since more than one group will use the FTIR spectrometer during the semester, the ATR cell has to be portable, and easy installation and removal are important design criteria. The instructor will provide an ATR crystal for the group as a starting point for developing the ATR cell. Once the cell is completed and tested, you will perform experiments with several liquid samples.

The second task of the project is to learn the basics of the programming system LABVIEW and to program a control interface for the LEYBOLD mass spectrometer (manuals and basic software tools will be provided). This program will also manage the heating controller for thermal desorption spectroscopy. Both instruments communicate with a Power MAC via a serial port interface. Groups #1 and #2 will depend on the timely “delivery” of this program package, since they will use the interface to take valuable thermal desorption data. Therefore, coordination of the time schedules between all groups is necessary and should be performed by the leaders of each group.

Figure 1. Information given to the students of Group 3 at the beginning of the course.
out of commercially available optical elements. ATR spectroscopy was chosen because it is an effective method for liquid IR sampling, sample liquids are easy to handle, and the overall cell design can be relatively simple. Design constraints given to the students in advance were that the cell must fit into the sample compartment of the available Nicolet 550 FTIR spectrometer. In addition, the instructors had ordered a 45° trapezoidal zinc selenide (ZnSe) crystal of dimensions 50x20x2 mm as the ATR element to avoid major time delays for the students. The ATR cell had to be easily removable from the sample compartment, since Project 2 also made use of the FTIR spectrometer during class periods. A starting budget of $1,000 was given to the group.

The secondary objective of this project included the implementation of a temperature controller and a mass spectrometer data acquisition module in LABVIEW®. This addition to the main project was chosen to bridge time gaps while the group was waiting for parts ordered or being machined. Figure 1 shows the original project description given to the students during the first class period.

In the beginning, the students felt this project assignment would be almost impossible to accomplish. None of the students in the group had any research-based experience with IR vibrational spectroscopy or design of optical components. The students set out to find information about IR spectroscopy in general and publications about other ATR cell designs. Their first thought was to find other designs in the scientific literature or manufacturer's catalogs and to simply "copy" one of them. They soon realized that the available information in the literature was sparse and the majority of the descriptions were not useful in designing their own cell.

During this first week, the instructor (who had done a literature research prior to the class) was available for discussions when students needed him, but he did not interfere or direct the information-gathering process. The students realized that they had to start their own thinking process, which required a better understanding of the underlying physical principles.

The group started to postulate design concepts. During this phase, it was important for the instructor to give suggestions while preserving the students' freedom to develop and pursue their own ideas. For example, the students soon found out that it is necessary to focus the IR beam on the entrance slit of the ATR crystal and immediately associated "focus" with "lens." Therefore, their first idea was to use silica or plastic lenses in their design. At this point, the instructor had to alert the students to the fact that lenses for IR wavelengths have to be made out of special materials in order to be transparent.

After the students had been encouraged to look at other IR beam designs and at the FTIR spectrometer in the lab, they came to the conclusion that gold-coated focusing mirrors would be the way to go. Further problems that had to be solved were the construction of the liquid sample holder and the holders for the optical components. Several design iterations and many discussions followed. After three weeks, the students had decided on their final design, which allowed them to stay within the budget. This group finished their design and construction of an ATR cell (shown in Figure 2), the total cost of which was about 30% of commercially available cells!

Students and instructors agreed that the final term paper should be written in the form of a scientific paper, which could be submitted to a scientific journal. After the cell design was finished and the cell was extensively tested with IR grade fluids, the students had eight lab periods left in the semester to perform experiments, which they planned on their own. For most of them, this high degree of freedom was unique compared with previous experiences in other laboratory classes. The group chose to compare various grades of gasoline, which they collected from local gas stations.

We think that the possibility of performing experiments with the equipment they designed and built is important in making this course a satisfying experience for students. Therefore, progress of the students should be monitored closely by the instructors to ensure that design and construction are finished with at least four weeks left in the semester.

**EDUCATIONAL ASPECTS**

During the semester, the students were closely monitored by an educational researcher from the Division of Chemical Education in the Department of Chemistry at Purdue University. The project evaluation was done using Action Research as the methodology. Qualitative Action Research is an informal, formative, interpretive, and experiential model of inquiry in which everyone involved in the study is an active, knowing participant. The knowledge sought was
"what worked and why," and "what needs to be changed for the next class?" The educational researcher spent every moment he could with the students and the instructors during the scheduled class time. Data were collected from a variety of sources, including oral and written field notes, video tapes of the presentations and lectures, group lab reports, student written evaluations, student interviews, and conversations with the instructor. Oral data were transcribed for analysis, and inductive analysis was used to find emergent patterns in the data. Inductive analysis is a method used in qualitative research that allows meaningful categories and themes to develop from the raw data, such as transcriptions and field notes. Reading, categorizing, and re-categorizing data patterns through the whole evaluation period over time allowed the students' and instructor's words, actions, and interests to become clearly organized into knowledge claims that could inform the instructional practice of the course. Four emergent knowledge claims at the writing of this paper are:

1. Groups that are mixed by academic experience can work well and benefit everyone.

The factor that added the highest degree of complexity to the course was the mixture of undergraduate students and graduate students in each group. The groups were allowed to negotiate for themselves who would be the group leader. A graduate student emerged as the group leader in each group, but the interpretation of what it meant to be a leader varied in each group. Due to the long-term nature of the projects, everyone in each group needed and gained a basic understanding of every aspect of their group's project. The undergraduates attributed much of their self-improvement in their technical writing skills and experimentation skills from working with graduate students as peers in their groups. Due to the collaborative nature of the projects, full participation in every aspect of the group's project was required of each group member, and for the most part undergraduate and graduate students took over equal research responsibilities. One graduate student commented, "It would have been impossible for one of us to have done all the work and come up with all the ideas. I have my own research to do. The undergraduates worked really well with us." Most of the cooperative learning literature is devoted to groups of the same age, grade, or course level. In this course, not only was there a horizontal relationship among the students due to the different areas of study, but also there was a perceived vertical relationship due to academic experience status.

2. The traditional roles of leader, experimentalist, and analyst were initially assigned, but the borderlines between these categories were often crossed.

In order for the groups to function properly, every member of each group needed to develop a basic understanding of every aspect of the group's project. Due to the large nature of the projects, no one person (including the instructor)

| Assertion 1 |

- "Having graduate and undergraduate students in the same group was a definite benefit. The diversity was something that we (undergraduate students) never would have experienced otherwise. Working with them allowed us the chance to benefit from their skills. Now I know that there are real people behind those doors in the building. I know more now what they do and how they approach problems."
- "The course could be divided into undergraduate and graduate students, with the undergraduates working in a more controlled environment. The course went fine, but it would be interesting to see what the graduate students could do if they were by themselves."

| Assertion 2 |

- "We tried to keep the roles through the first paper, but they just didn't work out, except for the group leader. That was something that stayed the same."
- "I wrote up a complete section of the second paper on TPD from the background and theory to our experiments. I was an analyst at the first, but I guess we all kind of ... took care of our own areas. The roles didn't do too much for us."
- "I have learned lots of lab techniques and benefited from working with others who are not in my major, learned to see things from a different point of view. As well I have learned things that I hadn't expected like how to use what I know and combine it with what I don't know, and what my group members know to solve a problem."

| Assertion 3 |

- "I have increased my problem solving abilities. My analytical thinking has changed as well as how I look at things. See the forest not the trees."
- "I think one of the best qualities of this course was the flexibility given to the students on the projects. To actually plan, design, construct, and implement a tool is very rewarding. The very fact that the design begins from scratch forces us to understand every part of the process."

| Assertion 4 |

- "The presentations were good. We got to see what other people were doing instead of just hearing about our own project. The other groups were doing some things that related to our experiments."
- "The discussions and lectures were okay. Sometimes they went a little long and cut into our lab time. That made it difficult some days when you only had a certain number of days on the equipment."
- "My technical writing has greatly improved. Working with the graduate student helped, and I got to be sort of an 'expert' on a process and a piece of equipment."

| TABLE 3 |

| Student Comments |

- "In other unit-ops labs they [the instructors] set the standards, or they have been set since time began. Here we set our own standards and deal with problems that come up. It's up to us to fix them."
- "I think the freedom and responsibility we had in the course is one of the greatest parts of it. We were able to do what we needed to do to solve the problems to reach our goals."

264 Chemical Engineering Education
could have made all of the content, design factor, and experimental design decisions for the group. Each member of the group was required to make two presentations during the semester, a task usually assigned to the group leader in traditional laboratory courses. Therefore, the members of each group became “experts” on a particular instrument, content, or experimental process. Each member of the group was involved in the experimentation and/or analysis of each aspect of the project. Although there was a graduate student in each group who served as a group leader, each described his/her role as more of a group-organizer/facilitator than as a leader who told everyone what to do.

3. The written reports and presentations afforded the students freedom to improve their own knowledge throughout the semester.

The groups were required to turn in three formal written reports during the semester. An exciting observation was made after the first reports were graded and handed back to the students: the students separated the graded reports into sections for each group member to work on; the comments and suggestions written on their reports were used to improve their existing experimental procedures and to improve their technical writing in subsequent papers. The researcher had never observed this in the traditional chemical engineering laboratory classrooms. The students, especially the undergraduates, gave great praise to the Tuesday-morning presentation time, which obviously helped them to improve their own presentation skills. But the students also said that this time helped them improve their “presentation listening/comprehension” ability. By listening to all of the presentations from each group, the students were exposed to a greater knowledge base than if they had only heard the presentations from their particular group. Many of the “Five-Minute/One Overhead” talks were followed by 10-15 minutes of questions and discussion. Two undergraduates, however, felt intimidated due to the content level of questions and discussion. Their major complaint was that the questions and discussion were sometimes based on knowledge that was neither based on nor developed in the course itself. The remainder of the undergraduates also felt a similar degree of intimidation, but realized that research is not exactly like a classroom; one undergraduate noted, “You have to utilize knowledge from wherever you can.”

The setting of the Tuesday-morning talks was also important. The setting was not a classroom, but a conference room. Instead of sitting in desks, all facing the front, everyone sat in comfortable chairs arranged in a “U.” This provided an atmosphere that was more like a community of researchers rather than a classroom of individuals.

4. The students used their experimental freedom for taking ownership and responsibility for their own knowledge and skills.

In each of the interviews, the students praised the freedom that the design of this course allowed them to have, as compared with traditional laboratory courses they had experienced. This course allowed them to “set their own standards,” “set and achieve their own goals,” and “make mistakes, and change things to fix them.” The students described other laboratory courses as “being told what to do” in order to “give them [the instructors] what they wanted for the points.” Other representative comments can be found in Table 3.

CONCLUDING REMARKS

We have reported a novel approach to laboratory teaching for undergraduate and graduate students providing degrees of research freedom atypical for chemical engineering laboratory instruction. Judging from our experience with this course and the student feedback, we can conclude that the approach provides valuable training for every student interested in learning more about experimental work. We expect the course to become an elective course in Purdue’s chemical engineering curriculum. The concept is portable to other universities. The main ingredient is a cluster of interested and experimentally oriented faculty willing to design course projects and seek the optimum level of monitoring to maximize student success in independent work. The scope of projects will, of course, depend on equipment available for student use. As with any new course, the faculty time commitment is largest the first time through when all the projects are new and untested.

ACKNOWLEDGMENTS

We are grateful to the Dow Chemical Company for its interest in, commitment to, and financial support of this educational investment in future experimentalists. We also thank Dr. David Taylor in the School of Chemical Engineering for assistance in specifying and setting up instrumentation.

REFERENCES

I • N • D • E • X

GRADUATE SCHOOL ADVERTISEMENTS

Akron, University of ................................................. 268
Alabama, University of ............................................. 269
Alberta, University of .............................................. 270
Arizona, University of .............................................. 271
Arizona State University ............................................ 272
Auburn University ..................................................... 273
Brigham Young University .......................................... 274
British Columbia, University of ................................... 275
Brown University ..................................................... 276
Bucknell University ................................................... 277
Calgary, University of ................................................ 278
California-Berkeley, University of ................................. 279
California-Davis, University of .................................... 280
California-Irving, University of .................................... 281
California-Los Angeles, University of ............................... 282
Clarkson University ................................................... 283
Clemson University ................................................... 284
Colorado State University ........................................... 285
Colorado School of Mines ............................................ 286
Colorado State University ........................................... 287
Columbia University .................................................. 288
Connecticut, University of .......................................... 289
Cornell University ..................................................... 290
Dartmouth College .................................................... 291
Delaware, University of ............................................. 292
Drexel University ...................................................... 293
Edinburgh, University of ........................................... 294
Florida, University of ............................................... 295
Florida A&M/Florida State University ............................... 296
Florida Institute of Technology ..................................... 297
Georgia Institute of Technology ................................... 298
Howard University .................................................... 299
Idaho, University of .................................................. 300
Illinois-Chicago, University of ..................................... 301
Illinois-Urbana, University of ...................................... 302
Illinois Institute of Technology ................................... 303
Imperial College ....................................................... 304
Iowa, University of ................................................... 305
Iowa State University ................................................ 306
Johns Hopkins University ........................................... 307
Kansas, University of ................................................ 308
Kansas State University ............................................. 309
Kentucky, University of ............................................. 310
Lamar University ...................................................... 311
Laval University ....................................................... 312
Lehigh University ..................................................... 313
Loughborough University ........................................... 314
Louisiana State University ......................................... 315
Louisiana Tech University .......................................... 316
Louisville, University of ............................................ 317
Maine, University of .................................................. 318
Manhattan University ............................................... 319
Maryland-Baltimore County, University of ....................... 320
Maryland, University of ............................................. 321
Massachusetts, University of ....................................... 322
<table>
<thead>
<tr>
<th>Institution</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massachusetts-Lowell, University of</td>
<td>380</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>315</td>
</tr>
<tr>
<td>McMaster University</td>
<td>369</td>
</tr>
<tr>
<td>Michigan, University of</td>
<td>516</td>
</tr>
<tr>
<td>Michigan State University</td>
<td>317</td>
</tr>
<tr>
<td>Michigan Technological University</td>
<td>318</td>
</tr>
<tr>
<td>Minnesota, University of</td>
<td>319</td>
</tr>
<tr>
<td>Missouri-Columbia, University of</td>
<td>369</td>
</tr>
<tr>
<td>Missouri-Rolla, University of</td>
<td>320</td>
</tr>
<tr>
<td>Monash University</td>
<td>370</td>
</tr>
<tr>
<td>Montana, University of</td>
<td>380</td>
</tr>
<tr>
<td>Nebraska, University of</td>
<td>321</td>
</tr>
<tr>
<td>New Jersey Institute of Technology</td>
<td>322</td>
</tr>
<tr>
<td>New Mexico, University of</td>
<td>323</td>
</tr>
<tr>
<td>New Mexico State University</td>
<td>370</td>
</tr>
<tr>
<td>New South Wales, University of</td>
<td>371</td>
</tr>
<tr>
<td>North Carolina A&amp;T State University</td>
<td>371</td>
</tr>
<tr>
<td>North Carolina State University</td>
<td>324</td>
</tr>
<tr>
<td>North Dakota, University of</td>
<td>380</td>
</tr>
<tr>
<td>Northeastern University</td>
<td>372</td>
</tr>
<tr>
<td>Northwestern University</td>
<td>325</td>
</tr>
<tr>
<td>Notre Dame, University of</td>
<td>326</td>
</tr>
<tr>
<td>Ohio State University</td>
<td>327</td>
</tr>
<tr>
<td>Ohio University</td>
<td>328</td>
</tr>
<tr>
<td>Oklahoma, University of</td>
<td>329</td>
</tr>
<tr>
<td>Oklahoma State University</td>
<td>330</td>
</tr>
<tr>
<td>Oregon State University</td>
<td>331</td>
</tr>
<tr>
<td>Ottawa, University of</td>
<td>372</td>
</tr>
<tr>
<td>Pennsylvania, University of</td>
<td>332</td>
</tr>
<tr>
<td>Pennsylvania State University</td>
<td>333</td>
</tr>
<tr>
<td>Pittsburgh, University of</td>
<td>334</td>
</tr>
<tr>
<td>Polytechnic University</td>
<td>335</td>
</tr>
<tr>
<td>Princeton University</td>
<td>373</td>
</tr>
<tr>
<td>Purdue University</td>
<td>336</td>
</tr>
<tr>
<td>Queensland, University of</td>
<td>337</td>
</tr>
<tr>
<td>Rensselaer Polytechnic Institute</td>
<td>338</td>
</tr>
<tr>
<td>Rhode Island, University of</td>
<td>373</td>
</tr>
<tr>
<td>Rice University</td>
<td>339</td>
</tr>
<tr>
<td>Rochester, University of</td>
<td>340</td>
</tr>
<tr>
<td>Rose-Hulman Institute of Technology</td>
<td>374</td>
</tr>
<tr>
<td>Rutgers University</td>
<td>341</td>
</tr>
<tr>
<td>South Carolina, University of</td>
<td>342</td>
</tr>
<tr>
<td>South Dakota School of Mines</td>
<td>380</td>
</tr>
<tr>
<td>South Florida, University of</td>
<td>374</td>
</tr>
<tr>
<td>Southern California, University of</td>
<td>375</td>
</tr>
<tr>
<td>State University of New York, Buffalo</td>
<td>375</td>
</tr>
<tr>
<td>Stevens Institute of Technology</td>
<td>343</td>
</tr>
<tr>
<td>Sydney, University of</td>
<td>376</td>
</tr>
<tr>
<td>Syracuse University</td>
<td>376</td>
</tr>
<tr>
<td>Tennessee, University of</td>
<td>344</td>
</tr>
<tr>
<td>Texas, University of</td>
<td>345</td>
</tr>
<tr>
<td>Texas A&amp;M University</td>
<td>346</td>
</tr>
<tr>
<td>Texas A&amp;M University-Kingsville</td>
<td>377</td>
</tr>
<tr>
<td>Toledo, University of</td>
<td>347</td>
</tr>
<tr>
<td>Tufts University</td>
<td>348</td>
</tr>
<tr>
<td>Tulane University</td>
<td>349</td>
</tr>
<tr>
<td>Tulsa, University of</td>
<td>350</td>
</tr>
<tr>
<td>Utah, University of</td>
<td>377</td>
</tr>
<tr>
<td>Vanderbilt University</td>
<td>351</td>
</tr>
<tr>
<td>Virginia, University of</td>
<td>352</td>
</tr>
<tr>
<td>Virginia Tech</td>
<td>353</td>
</tr>
<tr>
<td>Washington, University of</td>
<td>354</td>
</tr>
<tr>
<td>Washington State University</td>
<td>355</td>
</tr>
<tr>
<td>Washington University</td>
<td>356</td>
</tr>
<tr>
<td>Waterloo, University of</td>
<td>378</td>
</tr>
<tr>
<td>Wayne State University</td>
<td>357</td>
</tr>
<tr>
<td>West Virginia University</td>
<td>358</td>
</tr>
<tr>
<td>Widener University</td>
<td>378</td>
</tr>
<tr>
<td>Wisconsin, University of</td>
<td>359</td>
</tr>
<tr>
<td>Worcester Polytechnic Institute</td>
<td>360</td>
</tr>
<tr>
<td>Wyoming, University of</td>
<td>361</td>
</tr>
<tr>
<td>Yale University</td>
<td>362</td>
</tr>
</tbody>
</table>
Graduate Education in Chemical Engineering
at
The University of Akron

Faculty and Research Areas

G. A. ATWOOD
Digital Control, Mass Transfer, Multicomponent Adsorption

G. G. CHASE
Multiphase Processes, Heat Transfer, Interfacial Phenomena

H. M. CHEUNG
Colloids, Light Scattering Techniques

S. C. CHUANG
Catalysis, Reaction Engineering, Combustion, Environmentally Benign Synthesis

J. R. ELLIOTT
Thermodynamics, Material Properties

E. A. EVANS
Materials Processing and CVD Modeling

L. G. FOCHT
Fixed Bed Adsorption, Process Design

K. L. FULLERTON
Fuel Technology, Process Engineering, Environmental Engineering

M. A. GENCER
Biochemical Engineering, Environmental Biotechnology

L. K. JU
Biochemical Engineering, Environmental Bioengineering

S. LEE
Fuel and Chemical Process Engineering, Reactive Polymers, Waste Clean-Up

S. T. LOPINA
BioMateria Engineering and Polymer Engineering

H. C. QAMMAR
Nonlinear Control, Chaotic Processes

R. W. ROBERTS
Plastics Processing, Polymer Films, System Design

1 Professor Emeritus  2 Adjunct Faculty Member

Graduate assistant stipends for teaching and research start at $7,500.

Industrially sponsored fellowships available up to $17,000.

In addition to stipends, tuition and fees are waived.

PhD students may get some incentive scholarships.

The deadline for assistantship applications is March 15th.

Cooperative Graduate Education Program is also available.

For Additional Information, Write

Chairman, Graduate Committee

Department of Chemical Engineering • The University of Akron • Akron, OH 44325-3906
A dedicated faculty with state-of-the-art facilities offer research programs leading to Master of Science and Doctor of Philosophy degrees.

**Research Interests:**


**For Information Contact:**

Director of Graduate Studies  
Department of Chemical Engineering  
The University of Alabama  
Box 870203  
Tuscaloosa, AL 35487-0203  
Phone: (205) 348-6450

**Faculty**

G.C. April, Ph.D. (Louisiana State)  
D. W. Arnold, Ph.D. (Purdue)  
E. S. Carlson, Ph.D. (Wyoming)  
P. E. Clark, Ph.D. (Oklahoma State)  
W. C. Clements, Jr., Ph.D. (Vanderbilt)  
R. W. Flumerfelt, Ph.D. (Northwestern)  
R. A. Griffin, Ph.D. (Utah State)  
I. A. Jefcoat, Ph.D. (Clemson)  
P. W. Johnson, Ph.D. (New Mexico Tech.)  
A. M. Lane, Ph.D. (Massachusetts)  
M. D. McKinley, Ph.D. (Florida)  
R. G. Reddy, Ph.D. (Utah)  
L. Y. Sadler III, Ph.D. (Alabama)  
V. N. Schrod, Ph.D. (Penn. State)  
J. M. Wiest, Ph.D. (Wisconsin)
The University of Alberta is well known for its commitment to excellence in teaching and research. The Department of Chemical and Materials Engineering has 34 professors and over 100 graduate students. Degrees are offered at the M.Sc. and Ph.D. levels in Chemical Engineering, Materials Engineering, and Process Control. All full-time graduate students in the research programs receive a stipend to cover living expenses and tuition.

For further information, contact

Graduate Program Officer WCM
Department of Chemical and Materials Engineering
University of Alberta
Edmonton, Alberta, Canada T6G 2G6
PHONE (403) 492-5805 • FAX (403) 492-2881
e-mail: chemical.engineering@ualberta.ca
web: www.ualberta.ca/dept/chemeng
CHEMICAL AND ENVIRONMENTAL ENGINEERING
at
THE UNIVERSITY OF ARIZONA

The Chemical and Environmental Engineering Department at the University of Arizona offers a wide range of research opportunities in all major areas of chemical engineering and environmental engineering, and graduate courses are offered in most of the research areas listed here. The department offers a fully accredited undergraduate degree as well as MS and PhD graduate degrees. Strong interdisciplinary programs exist in bioprocessing and bioseparations, microcontamination in electronics manufacture, and environmental process modification.

Financial support is available through fellowships, government and industrial grants and contracts, teaching and research assistantships.

Tucson has an excellent climate and many recreational opportunities. It is a growing modern city of 450,000 that retains much of the old Southwestern atmosphere.
CHEMICAL, BIO, AND MATERIALS ENGINEERING AT

ARIZONA

STATE

UNIVERSITY

Chemical Engineering

Beaudoin, Stephen P., Ph.D., North Carolina State University • Transport Phenomena and Surface Science concerning Pollution Prevention, Waste Minimization, and Pollution Remediation
Beckman, James R., Ph.D., University of Arizona • Crystallization and Solar Cooling
Bellamy, Lynn, Ph.D., Tulane • Process Simulation
Berman, Neil S., Ph.D., University of Texas, Austin • Fluid Dynamics and Air Pollution
Burrows, Veronica A., Ph.D., Princeton University • Surface Science, Semiconductor Processing
Cale, Timothy S., Ph.D., University of Houston • Catalysis, Semiconductor Processing
Garcia, Antonio A., Ph.D., UC, Berkeley • Acid-Base Interactions, Biochemical Separation, Colloid Chemistry
Kuester, James L., Ph.D., Texas A&M University • Thermochemical Conversion, Complex Reaction Systems
Raupp, Gregory B., Ph.D., University of Wisconsin • Semiconductor Materials Processing, Surface Science, Catalysis
Rivera, Daniel, Ph.D., Cal Tech • Process Control and Design
Sater, Vernon E., Ph.D., Illinois Institute of Tech • Heavy Metal Removal from Waste Water, Process Control
Torrest, Robert S., Ph.D., University of Minnesota • Multiphase Flow, Filtration, Flow in Porous Media, Pollution Control

Bioengineering

Dorson, William J., Ph.D., University of Cincinnati • Physicochemical Phenomena, Transport Processes
Guilbeau, Eric J., Ph.D., Louisiana Tech University • Biosensors, Physiological Systems, Biomaterials
He, Jiping, Ph.D., University of Maryland • Biomechanics, Robotics, Computational Neuroscience, Optimal Control, System Dynamics and Control
Kipke, Daryl R., Ph.D., University of Michigan • Computation Neuroscience • Machine Vision, Speech Recognition, Robotics • Neural Networks
Pizziconi, Vincent B., Ph.D. Arizona State University • Artificial Organs, Biomaterials, Bioseparations
Sweeney, James D., Ph.D., Case-Western Reserve University • Rehab Engineering, Applied Neural Control
Towe, Bruce C., Ph.D., Pennsylvania State University • Bioelectric Phenomena, Biosensors, Biomedical Imaging
Yamaguchi, Gary T., Ph.D., Stanford University • Biomechanics, Rehab Engineering, Computer-Aided Surgery

Materials Science & Engineering

Adams, James, Ph.D., University of Wisconsin, Madison • Atomistic Simulation of Metallic Surfaces • Grain Boundaries • Automobile Catalysts • Polymer-Metal Adhesion
Alford, Terry L., Ph.D., Cornell University • Electronic Materials • Physical Metallurgy • Electronic Thin Films • Surface/Thin Film
Carpenter, Ray W., Ph.D., University of California, Berkeley • Atomic Structure and Chemistry of Interfaces and Boundaries in Solids; Phase Transformation Mechanisms in Metals and Ceramics; Electron Microscopy Methods and Instrumentation
Dey, Sandip K., Ph.D., NYSC of Ceramics, Alfred University • Ceramics, Sol-Gel Processing
Mahajan, Subhash, Ph.D., University of Michigan • Semiconductor Defects, Structural Materials Deformation
Mayer, James, Ph.D., Purdue University • Thin Film Processing • Ion Beam Modification of Materials
Stanley, James T., Ph.D., University of Illinois • Phase Transformations, Corrosion

For more details regarding the graduate degree programs in the Department of Chemical, Bio, and Materials Engineering, please call (602) 965-3313 or write to: Dr. Eric Guilbeau, Chair of the Graduate Committee, Department of Chemical, Bio, and Materials Engineering, Arizona State University, Tempe, Arizona 85287-6006.
Research Areas

- Biochemical Engineering • Biotechnology
- Pulp and Paper • Process Control
- Catalysis and Reaction Engineering
- Computer Aided Process Synthesis, Optimization and Design
- Environmental Chemical Engineering
- Pollution Prevention • Recycling
- Materials • Polymers • Surface Science
- Colloid and Interfacial Phenomena
- Thermodynamics • Supercritical Fluids
- Separation • Electrochemical Engineering
- Fluid Dynamics and Transport Phenomena
  • Fuels and Energy
The Department offers graduate programs leading to the M.Sc. and Ph.D. degrees in Chemical Engineering (full-time) and the M.Eng. degree in Chemical Engineering, Petroleum Reservoir Engineering or Engineering for the Environment (part-time) in the following areas:

- Biochemical Engineering & Biotechnology
- Biomedical Engineering
- Environmental Engineering
- Modeling, Simulation & Control
- Petroleum Recovery & Reservoir Engineering
- Process Development
- Reaction Engineering/Kinetics
- Thermodynamics
- Transport Phenomena

Fellowships and Research Assistantships are available to all qualified applicants.

*For Additional Information Write*

Dr. A. K. Mehrotra • Chair, Graduate Studies Committee
Department of Chemical and Petroleum Engineering
The University of Calgary • Calgary, Alberta, Canada T2N 1N4

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 center. Beautiful Banff National Park is 110 km west of the City and the ski resorts of Banff, Lake Louise, and Kananaskis areas are readily accessible. In the above photo the University Campus is shown with the Olympic Oval and the student residences in the foreground. The Engineering complex is on the left of the picture.
The UNIVERSITY OF CALIFORNIA at 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

Biochemical Engineering
Electrochemical Engineering
Electronic Materials Processing
Energy Utilization
Fluid Mechanics
Kinetics and Catalysis
Polymer Science and Technology
Process Design and Development
Separation Processes
Surface and Colloid Science
Thermodynamics

FACULTY

ALEXIS T. BELL
HARVEY W. BLANCH (Chair)
ELTON J. CAIRNS
ARUP K. CHAKRABORTY
DOUGLAS S. CLARK
MORTON M. DENN
SIMON L. GOREN
DAVID B. GRAVES
ENRIQUE IGLESIA

JAY D. KEASLING
C. JUDSON KING
ROYA MABoudIAN
SUSAN J. MULLER
JOHN S. NEwMAN
JOHN M. PRAUSNITZ
CLAYTON J. RADKE
JEFFREY A. REIMER

PLEASE WRITE:
DEPARTMENT OF CHEMICAL ENGINEERING • UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720-1462
University of California Davis

Department of Chemical Engineering & Materials Science

Offering M.S. and Ph.D. degree programs in both Chemical Engineering and Materials Science and Engineering

Faculty

Nicholas L. Abbott, Associate Professor • Ph.D., Massachusetts Institute of Technology, 1991 • Nanomaterials

David E. Block, Assistant Professor • Ph.D., University of Minnesota, 1992 • Industrial fermentation, biochemical processes in pharmaceutical industry

Rober H. Boulton, Professor • Ph.D., University of Melbourne, 1976 • Fermentation and reaction kinetics, crystallization

Stephanie R. Dungan, Associate Professor • Ph.D., Massachusetts Institute of Technology, 1992 • Micelle transport, colloid and interfacial science in food processing

Bruce C. Gates, Professor • Ph.D., University of Washington, Seattle, 1966 • Catalysis, solid superacid catalysis, zeolite catalysts, biomass catalysis, catalysis by metal clusters

Jeffrey C. Gibling, Professor • Ph.D., Stanford University, 1979 • Deformation and fatigue of metals and metal matrix composites

Joanna E. Groza, Professor • Ph.D., Polytechnic Institute, Bucharest, 1972 • Plasma activated sintering and processing of nanostructured materials

Brian G. Higgins, Professor • Ph.D., University of Minnesota, 1980 • Fluid mechanics and interfacial phenomena, surfactant processing, coating flows

David G. Howitt, Professor • Ph.D., University of California, Berkeley, 1976 • Forensic and failure analysis, electron microscopy, ignition and combustion processes in materials

Alan P. Jackman, Professor • Ph.D., University of Minnesota, 1968 • Protein production in plant cell cultures, bioremediation

Marjorie L. Longs, Assistant Professor • Ph.D., University of California, Santa Barbara, 1993 • Hydrophobic protein design for active control, surfactant microstructure, and interaction of proteins and DNA with biological membranes

Benjamin J. McCoy, Professor • Ph.D., University of Minnesota, 1967 • Supercooled extraction, pollutant transport

Karen A. McDonald, Associate Professor • Ph.D., University of Maryland, College Park, 1985 • Plant cell culture bioprocessing algal cell cultures

Amiya K. Mukherjee, Professor • D.Phil., University of Oxford, 1962 • Superplasticity of intermetallic alloys and ceramics, high temperature creep deformation

Zahid A. Murid, Professor • Ph.D., University of California, Berkeley, 1963 • Combustion synthesis, multiayer combustion systems, functionally gradient materials

Alexandra Navrotsky, Professor • Ph.D., University of Chicago, 1967 • Thermodynamics and solid state chemistry; high temperature calorimetry

Ahmet N. Palazoglu, Professor • Ph.D., Rensselaer Polytechnic Institute, 1984 • Process control and process design of environmentally benign processes

Ronald J. Phillips, Associate Professor • Ph.D., Massachusetts Institute of Technology, 1980 • Transport processes in bioprocesses, bionanomaterials, and materials science

Robert J. Powell, Professor • Ph.D., Johns Hopkins University, 1978 • Rheology, suspension mechanics, magnetic resonance imaging of suspensions

Sabah H. Risbud, Professor and Chair • Ph.D., University of California, Berkeley, 1976 • Semiconductor quantum dots, high T, superconducting ceramics, polymer composites for optics

Dewey D. Ryu, Professor • Ph.D., Massachusetts Institute of Technology, 1967 • Biomolecular process engineering and recombinant bioprocess technology

James F. Shackleford, Professor • Ph.D., University of California, Berkeley, 1971 • Structure of materials, biomaterials, nondestructive testing of engineering materials

James H. Smith, Professor Emeritus • Sc.D., Massachusetts Institute of Technology, 1953 • Chemical kinetics and reactor design

Pieter Stroeve, Professor • Sc.D., Massachusetts Institute of Technology, 1973 • Membrane separations, Langmuir Blodgett films, colloid and surface science

Stephen Whitaker, Professor • Ph.D., University of Delaware, 1959 • Multiphase transport phenomena

The multifaceted graduate study experience in the Department of Chemical Engineering and Materials Science allows students to choose research projects and thesis advisors from any of our faculty with expertise in chemical engineering and/or materials science and engineering.

Our department faculty provide excellent access to the scientists and facilities at nearby National Laboratories (LBL and LLNL) and industry in the Silicon Valley and San Francisco Bay Area.

Davis is a small, bike-friendly university town located 17 miles west of Sacramento and 72 miles northeast of San Francisco, within driving distance of a multitude of recreational activities in Yosemite, Lake Tahoe, Monterey, and San Francisco Bay Area.

For information about our program, look up our website at http://www.chem.ucdavis.edu or contact us via e-mail at chmggrads@chem.ucdavis.edu

On-line applications may be submitted via https://secureweb.ucdavis.edu:2443

Graduate Admission Chair
Professor Ronald J. Phillips
Department of Chemical Engineering & Materials Science
University of California, Davis
Davis, CA 95616-5294, USA
Phone (916) 752-2803 • Fax (916) 752-1031

276
UNIVERSITY OF CALIFORNIA
IRVINE

PROGRAM
Offers degrees at the M.S. and Ph.D. levels. Research in frontier areas in chemical engineering, biochemical engineering, biotechnology and materials science and engineering. Strong physical and life science and engineering groups on campus.

LOCATION
The 1,510-acre UC Irvine campus is in Orange County, five miles from the Pacific Ocean and 40 miles south of Los Angeles. Irvine is one of the nation's fastest growing residential, industrial, and business areas. Nearby beaches, mountain and desert area recreational activities, and local cultural activities make Irvine a pleasant city in which to live and study.

For further information and application forms, please visit http://www.eng.uci.edu/cbe/or contact
Department of Chemical and Biochemical Engineering and Materials Science
School of Engineering
University of California
Irvine, CA 92697-2575

Fall 1997

Graduate Studies in
Chemical and Biochemical Engineering
and
Materials Science and Engineering
for Chemical Engineering, Engineering, and Science Majors

FACULTY

Nancy A. Da Silva (California Institute of Technology)
James C. Earthman (Stanford University)
Steven C. George (University of Washington)
Juan Hong (Purdue University)
Enrique J. Lavernia (Massachusetts Institute of Technology)
Henry C. Lim (Northwestern University)
Martha L. Mecartney (Stanford University)
Farhghali A. Mohamed (University of California, Berkeley)
Frank G. Shi (California Institute of Technology)
Thomas K. Wood (North Carolina State University)

Joint Appointments:
Roger H. Rangel (University of California, Berkeley)
William A. Sirignano (Princeton University)

RESEARCH AREAS

- Biomedical Engineering
- Bioreactor Engineering
- Bioremediation
- Ceramics
- Combustion
- Composite Materials
- Control and Optimization
- Environmental Engineering
- Interfacial Engineering
- Materials Processing
- Mechanical Properties
- Metabolic Engineering
- Microelectronics Processing and Modeling
- Microstructure of Materials
- Nanocrystalline Materials
- Nucleation, Chrystallization and Glass Transition Process
- Polymers
- Recombinant Cell Technology
- Separation Processes
- Sol-Gel Processing
- Two-Phase Flow
- Water Pollution Control
CHEMICAL ENGINEERING AT

UCLA

RESEARCH AREAS

• Molecular Simulations
• Thermodynamics and Cryogenics
• Process Design, Dynamics, and Control
• Polymer Processing and Transport Phenomena
• Kinetics, Combustion, and Catalysis
• Surface and Interface Engineering
• Electrochemistry and Corrosion
• Biochemical Engineering
• Aerosol Science and Technology
• Air Pollution Control and Environmental Engineering

PROGRAMS

UCLA's Chemical Engineering Department offers a program of teaching and research linking fundamental engineering science and industrial practice. Our Department has strong graduate research programs in environmental chemical engineering, biotechnology, and materials processing. With the support of the Parsons Foundation, The National Science Foundation, and the U.S. Department of Education, we are pioneering the development of methods for the design of clean chemical technologies, both in graduate research and engineering education.

Fellowships are available for outstanding applicants in both M.S. and Ph.D. degree programs. A fellowship includes a waiver of tuition and fees plus a stipend.

Located five miles from the Pacific Coast, UCLA's attractive 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

Panagiotis D. Christofides  
Y. Cohen
M. W. Deem
T. H. K. Frederking  
S. K. Friedlander
R. F. Hicks
E. L. Knuth  
(Prof. Emeritus)  
James C. Liao
V. Manousiouthakis
H. G. Monbouquette  
K. Nobe
L. B. Robinson  
(Prof. Emeritus)
S. M. Senkan
W. D. Van Vorst  
(Prof. Emeritus)  
V. L. Vilker  
(Prof. Emeritus)  
A. R. Wazzan

Fellowships are available for outstanding applicants in both M.S. and Ph.D. degree programs. A fellowship includes a waiver of tuition and fees plus a stipend.

Located five miles from the Pacific Coast, UCLA's attractive 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.

CONTACT

Admissions Officer • Chemical Engineering Department  
5531 Boelter Hall • UCLA • Los Angeles, CA 90095-1592  
(310) 825-9063

278  
Chemical Engineering Education
L. GARY LEAL Ph.D. (Stanford) (Chair) • Fluid Mechanics, Physics and Rheology of Complex Fluids, including Polymers, Suspensions, and Emulsions.

ERAY S. AYDIL Ph.D. (University of Houston) • Microelectronics and Plasma Processing.

SANJOY BANERJEE Ph.D. (Waterloo) • Environmental Fluid Dynamics, Multiphase Flows, Turbulence, Computational Fluid Dynamics.

BRADLEY F. CHMELKA Ph.D. (U.C. Berkeley) • Inorganic-Organic Hybrid Materials, Zeolites and Molecular Sieves, Polymeric Solids, Liquid Crystals, Solid-State NMR.

GLENN H. FREDRICKSON Ph.D. (Stanford) (Vice-Chair) • Statistical Mechanics, Glasses, Polymers, Composites, Alloys.

JACOB ISRAELACHVILI Ph.D. (Cambridge) • Surface and Interfacial Phenomena, Adhesion, Colloidal Systems, Surface Forces, Biomolecular Interactions, Friction.


FRED F. LANGE Ph.D. (Penn State) • Powder Processing of Composite Ceramics, Liquid Precursors for Ceramics, Superconducting Oxides.


DIMITRIOS MAROUDAS Ph.D. (M.I.T.) • Theoretical and Computational Materials Science, Microstructure Evolution in Electronic and Structural Materials.


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

DAVID J. PINE Ph.D. (Cornell) • Polymer, Surfactant, and Colloidal Physics, Multiple Light Scattering, Photonic Crystals, Macroporous Materials.

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

DALE E. SEBORG Ph.D. (Princeton) • Process Control, Monitoring and Identification.

T. G. THEOFANOUS Ph.D. (Minnesota) • Multiphase Flow, Risk Assessment and Management

W. HENRY WEINBERG Ph.D. (U.C. Berkeley) • Surface Chemistry, Heterogeneous Catalysis, Electronic Materials, Materials Discovery using Combinatorial Chemistry

JOSEPH A. ZASADZINSKI Ph.D. (Minnesota) • Surface and Interfacial Phenomena, Biomaterials.

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.

THE UNIVERSITY
One of the world’s few seashore campuses, UCSB is located on the Pacific Coast 100 miles northwest of Los Angeles. The student enrollment is over 18,000. 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

Chair • Graduate Admissions Committee • Department of Chemical Engineering • University of California • Santa Barbara, CA 93106

Fall 1997
Chemical Engineering at the

CALIFORNIA INSTITUTE OF TECHNOLOGY

"At the Leading Edge"

FACULTY

Frances H. Arnold  George R. Gavalas  David A. Tirrell
John F. Brady  Konstantinos P. Giapis  Nicholas W. Tschoegl (Emeritus)
Mark E. Davis  Julia A. Kornfield
Richard C. Flagan  John H. Seinfeld
Zhen-Gang Wang

RESEARCH INTERESTS

Aerosol Science  Colloid Physics
Applied Mathematics  Fluid Mechanics
Atmospheric Chemistry and Physics  Materials Processing
Biocatalysis and Bioreactor Engineering  Microelectronics Processing
Biomaterials  Microstructured Fluids
Bioseparations  Polymer Science
Catalysis  Protein Engineering
Chemical Vapor Deposition  Statistical Mechanics
Combustion

For further information, write ________________

Address: Director of Graduate Studies
Chemical Engineering 210-41 • California Institute of Technology • Pasadena, California 91125

Also, visit us on the World Wide Web for an on-line brochure: http://www.che.caltech.edu
POP INTO CARNEGIE MELLON

Who says you only get fifteen minutes of fame? As a graduate student in Carnegie Mellon's Department of Chemical Engineering, you can perform groundbreaking research in bioengineering, environmental engineering, process systems engineering, solid state materials, or complex fluids engineering. And be mentored by our contemporary faculty—who have made research a fine art.

For information, please write:
Director of Graduate Admissions
Department of Chemical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213-3890
412-268-2243
www.chem.cmu.edu
Students in the Department of Chemical Engineering are involved in state-of-the-art research. Here, two students make adjustments to a component of a prototype fuel cell.

Research Opportunities

- Low Pressure Growth of Diamonds
- Process Control
- Colloidal Phenomena and Microemulsions
- Electrochemical Engineering
- Biomedical Sensors
- Synthesis of Electronic Material
- Polymers and Interfacial Phenomena
- Fuel Cells
- Catalysis and Reactor Design
- Separation Processes
- Interfacial Transport and Liquid Crystals
- In Situ Diagnostics

For more information on Graduate Research, Admission, and Financial Aid, contact:

Graduate Coordinator
Department of Chemical Engineering
Case Western Reserve University
10900 Euclid Avenue
Cleveland, Ohio 44106-7217

or see our home page at

http://k2.scl.cwru.edu/cse/eche/

CWRU Chemical Engineering Education
Opportunities for Graduate Study in Chemical Engineering at the

UNIVERSITY OF CINCINNATI

M.S. and Ph.D. Degrees in Chemical Engineering

Faculty
Amy Ciric
Joel Fried
Stevin Gehrke
Rakesh Govind
David Greenberg
Daniel Hershey
Sun-Tak Hwang
Robert Jenkins
Yuen-Koh Kao
Soon-Jai Khang
Y. S. Lin
Neville Pinto
Sotiris Pratsinis
Peter Smirniotis

Financial Aid Available

The University of Cincinnati is committed to a policy of non-discrimination in awarding financial aid.

For Admission Information
Director, Graduate Studies
Department of Chemical Engineering
PO Box 210171
University of Cincinnati
Cincinnati, Ohio 45221-0171
e-mail: char@alpha.che.uc.edu

The faculty and students in the Department of Chemical Engineering are engaged in a diverse range of exciting research topics. A limited number of assistantships and tuition scholarships are available to highly qualified applicants to the MS and PhD degree programs.

- **Biotechnology (Bioseparations)**
  Novel bioseparation techniques, chromatography, affinity separations, biodegradation of toxic wastes, controlled drug delivery, two-phase flow, suspension rheology.

- **Chemical Reaction Engineering and Heterogeneous Catalysis**
  Modeling and design of chemical reactors, deactivation of catalysts, flow pattern and mixing in chemical equipment, laser induced effects.

- **Coal Research**
  New technology for coal combustion power plant, desulfurization and denitrification.

- **Material Synthesis**
  Manufacture of advanced ceramics, optical fibers and pigments by aerosol processes.

- **Membrane Separations**
  Membrane gas separations, membrane reactors, sensors and probes, pervaporation, dynamic simulation of membrane separators, membrane preparation and characterization for polymeric and inorganic materials, inorganic membranes.

- **Particle Technology**
  Flocculation of liquid suspensions, granulation of fine powders, grinding of agglomerate particles.

- **Polymers**
  Thermodynamics, polymer blends and composites, high-temperature polymers, hydrogels, rheology, computational polymer science.

- **Process Synthesis**
  Computer-aided design methodologies, design for waste minimization, design for dynamic stability, separation system synthesis.
Graduate Study in Chemical Engineering at Clarkson University

M.S., M.ENG., and PH.D. Programs

Teaching and Research Assistantships available to M.S. and Ph.D. students

Research Areas:
- Electrochemical Engineering
- Chemical Kinetics
- Chemical Metallurgy
- Nucleation
- Corrosion Engineering
- Crystal Growth
- Space Processing
- Process Control
- Fluid Mechanics
- Bubble Dynamics
- Heat Transfer
- Mass Transfer
- Laser and Plasma Technology
- Polymer Processing and Rheology
- Biochemical Engineering
- Process Design
- Solid State Reactions

For information, write to:
Dr. Anthony G. Collins
Dean of Engineering
Clarkson University
P.O. Box 5700
Potsdam, New York 13699-5700

315-268-7929
Fax: 315-268-3841
Email: schofeng@agent.clarkson.edu
World Wide Web: http://www.clarkson.edu

Clarkson University is a nondiscriminatory, affirmative action, equal opportunity educator and employer.
Tradition and Excellence Meet

For more than 100 years, engineering at Clemson University has distinguished itself by pursuing excellence through the combination of traditional education and innovative research programs. The Department of Chemical Engineering has continued in that vein by building very active research programs aimed at developing basic scientific understanding of critical engineering materials and technology. Additionally, students can participate in the department’s M.S. Industrial Residency Program, which combines on-campus course work with practical work assignments in industry. Students can conduct their thesis research under joint faculty and industrial supervision.

Clemson is a land-grant institution with an enrollment of more than 16,500 students, including 3,800 graduate students. The 1,400-acre main campus is located in the foothills of the Blue Ridge Mountains, on the shores of Lake Hartwell, midway between Atlanta, Ga., and Charlotte, N.C.

The Faculty

- Charles H. Barron, Jr.
- David A. Bruce
- Dan D. Edie
- Charles H. Gooding
- James M. Haile
- Douglas E. Hirt
- S. Michael Kilbey II
- Stephen S. Melsheimer
- Amod A. Ogale
- Richard W. Rice
- Mark C. Thies

Research Areas

- Catalysis
- Engineering
- Fibers & Films
- Interfacial Engineering
- Membrane Separations
- Molecular Dynamics
- Polymers & Composites
- Supercritical Fluids
- Water Remediation

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

For More Information, Contact: Graduate Coordinator, Department of Chemical Engineering, Clemson University, Box 340909, Clemson, SC 29634-0909, Telephone (864) 656-3055, Email address: che@eng.clemson.edu

Visit our Web site at www.ces.clemson.edu
RESEARCH INTERESTS

Biotechnology and Bioengineering
- Biomaterials and Biomechanics
- Biomedical Engineering
- Bioreactor Design and Optimization
- Purification and Formulation

Chemical Environmental Engineering
- Global Change
- Pollution Remediation
- Separations

Materials Science and Engineering
- Catalysis and Surface Science
- Advanced Ceramics Synthesis
- Colloidal Phenomena
- Polymerization Reaction Engineering
- Biomaterials

Membrane Science
- Chemically Specific Separations
- Membrane Transport and Separations
- Polymeric Membrane Morphology

Modeling and Control
- Expert Systems
- Mathematical Modeling
- Process Control and Identification

Transport Phenomena and Thermodynamics
- Fluid Dynamics
- Suspensions and Complex Fluids
- Supercritical Fluids
- Electrokinetics

FOR INFORMATION AND APPLICATION, WRITE TO
Graduate Admissions Committee • Department of Chemical Engineering
University of Colorado, Boulder • Boulder, Colorado 80309-0424
PHONE (303) 492-7471 • FAX (303) 492-4341 • E-MAIL Chemeng@spot.Colorado.edu

Further information is also available on our URL page on the World Wide Web at • http://spot.colorado.edu/~chemeng/Home.html
R. M. BALDWIN, Professor and Head; Ph.D., Colorado School of Mines. Fuels science and catalysis.

A. L. BUNGE, Professor; Ph.D., University of California, Berkeley. Absorption of chemicals in skin, pharmacokinetic modeling, risk assessment.

J.R. DORGAN, Associate Professor; Ph.D., University of California, Berkeley. Polymer science and engineering.

J. F. ELY, Professor; Ph.D., Indiana University. Molecular thermodynamics and transport properties of fluids.

J. H. GARY, Professor Emeritus; Ph.D., University of Florida. Petroleum refinery processing operations, heavy oil processing, thermal cracking, visbreaking and solvent extraction.

J.O. GOLDEN, Professor; Ph.D., Iowa State University. Hazardous waste processing, fluidization engineering, incineration.

M.S. GRABOSKI, Research Professor; Ph.D., Pennsylvania State University. Fuels synthesis and evaluation, engine technology, alternate fuels

A. J. KIDNAY, Professor and Graduate Dean; D.Sc., Colorado School of Mines. Thermodynamic properties of gases and liquids, vapor-liquid equilibria, cryogenic engineering.

D.W.M. MARR, Assistant Professor; Ph.D., Stanford. Interfacial statistical mechanics, complex fluids.

R.L. McCORMICK, Research Assistant Professor; Ph.D., Wyoming. Catalysis in fuel synthesis, air pollution control, fuel cells, low emissions fuels for internal combustion engines, coal science and processing, ion conducting solid catalysts and electrolytes, reactor design and fluidization.

J.T. McKINNON, Associate Professor; Ph.D., Massachusetts Institute of Technology. High temperature gas phase chemical kinetics, combustion, hazardous waste destruction.

R. L. MILLER, Associate Professor; Ph.D., Colorado School of Mines. Interdisciplinary curriculum development, innovative pedagogies, measures of intellectual development, psychological theories of learning, multiphase fluid mechanics

M. S. SELIM, Professor, Ph.D., Iowa State University. Heat and mass transfer with a moving boundary, sedimentation and diffusion of colloidal suspensions, heat effects in gas absorption with chemical reaction, entrance region flow and heat transfer, gas hydrate dissociation modeling, sweetening of natural gas using mixed amines, ink jet printing, synthesis of nano-size magnetic particles for color toner and laserjet printing applications, modeling of hydrocarbon cracking furnaces and simulation of ethylene plants.

E. D. SLOAN, JR., Weaver Distinguished Professor; Ph.D. Clemson University. Natural gas hydrates, phase equilibria, education methods research.

J. D. WAY, Associate Professor; Ph.D. University of Colorado. Novel separation processes, membrane science and technology, membrane reactors, ceramic and metal membranes, biopolymer adsorbents for adsorption of heavy metals.

C. A. WOLDEN, Assistant Professor; Ph.D., Massachusetts Institute of Technology. Electronic materials processing, gas-solid reaction dynamics.

D. T. WU, Assistant Professor; Ph.D. University of California, Berkeley. Polymers, powders, theory and simulation of complex fluids and materials, phase equilibria, controlled self-assembly.

V. F. YESAVAGE, Professor; Ph.D., University of Michigan. Vapor liquid equilibrium and enthalpy of polar associating fluids, equations of state for highly non-ideal systems, process simulation, environmental engineering, gas-liquid reactions.

For applications and further information on M.S. and Ph.D. programs, write

Chemical Engineering and Petroleum Refining • Colorado School of Mines • Golden, CO 80401

Fall 1997
M.S. and Ph.D. programs in chemical engineering

RESEARCH IN . . .

- Advanced Process Control
- Biochemical Engineering
- Biofuels
- Catalysis
- Chemical Thermodynamics
- Chemical Vapor Deposition
- Contaminant Transport
- Computational Fluid Dynamics
- Environmental Biotechnology
- Environmental Engineering
- Polymeric Materials
- Solar Cooling Systems
- Semiconductor Processing
- Thin Films
- Water Quality Monitoring

FINANCIAL AID AVAILABLE

Teaching and research assistantships paying a monthly stipend plus tuition reimbursement.

For applications and further information, write
Department of Chemical and Bioresource Engineering
Colorado State University
Fort Collins, CO 80523-1370

CSU is located in Fort Collins, a pleasant community of 100,000 people with the spirit of the West, the vitality of a growing metropolitan area, and the friendliness of a small town. Fort Collins is located about 65 miles north of Denver and is adjacent to the foothills of the Rocky Mountains. The climate is excellent, with 300 sunny days per year, mild temperatures, and low humidity. Opportunities for hiking, biking, camping, boating, fishing, and skiing abound in the immediate and nearby areas. The campus is within easy walking or biking distance of the town’s shopping areas and its Center for the Performing Arts.

FACULTY

Laurence A. Belfiore, Ph.D.
University of Wisconsin

David S. Dandy, Ph.D.
California Institute of Technology

Deanna S. Durnford, Ph.D.
Colorado State University

M. Nazmul Karim, Ph.D.
University of Manchester

Terry G. Lenz, Ph.D.
Iowa State University

James C. Linden, Ph.D.
Iowa State University

Jim C. Loftis, Ph.D.
Colorado State University

Carol M. McConica, Ph.D.
Stanford University

David B. McWhorter, Ph.D.
Colorado State University

Vincent G. Murphy, Ph.D.
University of Massachusetts

Allen L. Rakow, Sc.D.
Washington University

Kenneth F. Reardon, Ph.D.
California Institute of Technology

Robert C. Ward, Ph.D.
North Carolina State University

Ranil Wickramasinghe, Ph.D.
University of Minnesota
### UNIVERSITY OF CONNECTICUT

**Graduate Study in**

**Chemical Engineering**

<table>
<thead>
<tr>
<th>M.S. and Ph.D. Programs for Scientists and Engineers</th>
</tr>
</thead>
</table>

### FACULTY RESEARCH AREAS

**Luke E.K. Achenie, Ph.D., Carnegie Mellon University**
- Modeling and Optimization, Neural Networks, Process Control

**Thomas F. Anderson, Ph.D., University of California, Berkeley**
- Modeling of Separation Processes, Fluid-Phase Equilibria

**James P. Bell, Sc.D., Massachusetts Institute of Technology**
- Structure-Property Relations in Polymers and Composites, Adhesion

**Carroll O. Bennett, Professor Emeritus, PhD., Yale University**
- Catalysis, Chemical Reaction Engineering

**Douglas J. Cooper, Ph.D., University of Colorado**
- Process Modeling, Monitoring and Control

**Robert W. Coughlin, Ph.D., Cornell University**
- Biotechnology, Biochemical and Environmental Engineering, Catalysis, Kinetics, Separations, Surface Science

**Michael B. Cutlip, Ph.D., University of Colorado**
- Kinetics and Catalysis, Electrochemical Reaction Engineering, Numerical Methods

**Anthony T. DiBenedetto, University Professor Emeritus, Ph.D., University of Wisconsin**
- Composite Materials, Mechanical Properties of Polymers

**Can Erkey, Ph.D., Texas A&M University**
- Supercritical Fluids, Environmental Engineering, Multicomponent Diffusion and Mass Transfer

**James M. Fenton, Ph.D., University of Illinois, Urbana-Champaign**

**Suzanne (Schadel) Fenton, Ph.D., University of Illinois**
- Computational Fluid Dynamics, Turbulence, Two-Phase Flow

**Robert J. Fisher, Ph.D., University of Delaware**
- Biochemical Engineering and Environmental Biotechnology

**Joseph J. Helble, Ph.D., Massachusetts Institute of Technology**
- Air Pollution, Nanoscale Materials Synthesis and Characterization, Combustion

**G. Michael Howard, Professor Emeritus, Ph.D., University of Connecticut**
- Process Systems Analysis and Modeling, Process Safety, Engineering Education

**Herbert E. Klei, Professor Emeritus, Ph.D., University of Connecticut**
- Biochemical Engineering, Environmental Engineering

**Jeffrey T. Koberstein, Ph.D., University of Massachusetts**
- Polymer Blends/Compatibilization, Polymer Morphology, Polymer Surface and Interfaces

**Harold R. Kunz, Ph.D., Rensselaer Polytechnic Institute**
- Fuel Cells, Electrochemical Energy Systems

**Montgomery T. Shaw, Ph.D., Princeton University**
- Polymer Rheology and Processing, Polymer-solution Thermodynamics

**Donald W. Sundstrom, Professor Emeritus, Ph.D., University of Michigan**
- Environmental Engineering, Hazardous Wastes, Biochemical Engineering

**Robert A. Weiss, Ph.D., University of Massachusetts**
- Polymer Structure-Property Relationships, Ion-Containing and Liquid Crystal Polymers, Polymer Blends
At Cornell University, graduate students in chemical engineering have the flexibility to
design research programs that take full advantage of Cornell's unique interdisciplinary
environment and enable them to pursue individualized plans of study.

Cornell graduate programs may draw upon the resources of many excellent depart­
ments and NSF-sponsored research centers such as the Biotechnology Center, the Cornell
National Supercomputing Facility, and the Materials Science Center.

Degrees granted include Master of Engineering, Master of Science, and Doctor of
Philosophy. All Ph.D. students are fully funded with attractive stipends and tuition
waivers.

Research Areas

- Advanced Materials Processing
- Biochemical and Biomedical Engineering
- Fluid Dynamics, Stability, and Rheology
- Molecular Thermodynamics and Computer Simulation
- Polymer Science and Engineering
- Reaction Engineering: Surface Science, Kinetics, and Reactor Design

Situated in the scenic Finger Lakes region of New York State, the Cornell campus is one of
the most beautiful in the country. Students enjoy sailing, skiing, fishing, hiking, bicycling,
boating, wine-tasting, and many other activities.

For further information, write:
Graduate Field Representative, School of Chemical Engineering, Cornell University, 120 Olin Hall, Ithaca, NY 14853-5201,
e-mail: GFR@CHEME.CORNELL.EDU, or “visit” our World Wide Web server at: http://wwwcheme.cornell.edu

Distinguished Faculty

A. Brad Anton
Paulette Clancy
Claude Cohen
T. Michael Duncan
James R. Engstrom*
Emmanuel P. Giannelis
Keith E. Gubbins†
Peter Harriott
Donald L. Koch*
Kelvin H. Lee
Leonard W. Lion
Christopher K. Ober
William L. Olbricht
Athanasios Panagiotopoulos*
Ferdinand Rodriguez
W. Mark Saltzman
Michael L. Shuler‡*
Paul H. Steen

* recipient, NSF PYI Award
† member, National Academy of Engineering
‡ member, American Academy of Arts & Science
Faculty

Mark A. Barteau
Antony N. Beris
Kenneth B. Bischoff
Douglas J. Buttry
Stuart L. Cooper
Nily R. Dan
Costel D. Denson
Prasad S. Dhurjati
Francis J. Doyle III
Henry C. Foley
Marylin C. Huff
Eric W. Kaler
Michael T. Klein
Abraham M. Lenhoff
Raul F. Lobo
Roy L. McCullough
Arthur B. Metzner, Emeritus
Jon H. Olson
Anne Skaja Robinson
T.W. Fraser Russell
Stanley I. Sandler
Jerold M. Schultz
Annette D. Shine
Norman J. Wagner
Richard P. Wool
Andrew L. Zydney

Research Areas

Thermodynamics • Separation Processes •
Polymer Science and Engineering •
Fluid Mechanics and Rheology •
Transport Phenomena • Materials Science
and Metallurgy • Catalysis and Surface
Science • Reaction Kinetics • Reactor
Engineering • Process Control •
Semiconductor and Photovoltaic
Processing • Biomedical Engineering •
Biochemical Engineering •
Colloid and Surfactant Science

The University of Delaware offers
M.ChE and Ph.D. degrees in
Chemical Engineering.
Both degrees involve
research and course work
in engineering and related sciences.
The Delaware tradition
is one of strong
interdisciplinary research
on
both fundamental
and applied problems.

For more information and application materials, write

Graduate Advisor • Department of Chemical Engineering
University of Delaware • Newark, Delaware 19716
Modern Applications of Chemical Engineering

Graduate Study Leading to the MS and PhD

- FACULTY -

TIM ANDERSON • Semiconductor Processing, Thermodynamics

IOANNIS BITSANIS • Molecular Modeling of Interfaces

OSCAR D. CRISALLE • Electronic Materials, Process Control

RICHARD B. DICKINSON • Biomedical Engineering

ARTHUR L. FRICKE • Polymers, Pulp & Paper Characterization

GAR HOFFLUND • Catalysis, Surface Science

LEW JOHNS • Applied Mathematics, Dispersion

DALE KIRMSE • Computer Aided Design, Process Control

RANGA NARAYANAN • Transport Phenomena, Low Gravity Fluid Mechanics

MARK E. ORAZEM • Electrochemical Engineering, Semiconductor Processing

CHANG-WON PARK • Fluid Mechanics, Polymer Processing

RAJ RAJAGOPALAN • Colloid Physics, Particle Science

DINESH O. SHAH • Surface Sciences, Biomedical Engineering

SPYROS SVORONOS • Process Control, Biochemical Engineering

For more information, please write: _________________________
Graduate Admissions Coordinator • Department of Chemical Engineering
University of Florida • P.O. Box 116005 • Gainesville, Florida 32611-6005
Phone (352) 392-0881 • E-mail, chemical@eng.ufl.edu • Website, http://www.che.ufl.edu/che
Research and Graduate Studies in Chemical Engineering
Florida A&M University / Florida State University College of Engineering
MS. and Ph.D. Programs

Faculty

Rufina Alamo
Complutense University of Madrid

Pedro Arce
Purdue University

Ravindran Chella
University of Massachusetts

Wright Finney
Florida State University

Stephen J. Gibbs
University of Wisconsin

Eric Kalu
Texas A&M University

Bruce R. Locke
North Carolina State University

Srinivas Palanki
University of Michigan

Michael H. Peters
Ohio State University

Samuel Riccardi
Ohio State University

John C. Telotte
University of Florida

Jorge Viñals
University of Barcelona

G. Dale Wesson
Michigan State University

Faculty research interests

Advanced Materials
Composite materials and ceramics
Crystal growth
Dynamics of polymer blends and solutions under flow
Fluid mechanics of mixing
Polymer crystallization

Bio-engineering
Aerosol drug delivery systems
Dynamics and transport of biological macromolecules
Electrophoretic separation of biological molecules
Fermentation process
Lung contamination
Microhemodynamics
Transport in biological tissue

Process Control and Optimization
Nonlinear process control
Optimization of batch reactors

Reaction Science and Engineering
Corona reaction engineering
Electrochemical engineering
Polymer reaction and thermodynamics

Transport Processes
Molecular and macromolecular transport
Multi-phase flows and reaction
NMR imaging
Particle formation, transport and deposition
Nonlinear dynamics, pattern formation and chaos
Transport and reaction in porous media
Suspension rheology

Affiliated Research Programs
Geophysical Fluids Dynamics Institute
Institute for Molecular Biophysics
Materials Research and Technology Center
National High Magnetic Field Laboratory
Supercomputer Computations Research Institute
Graduate Studies in Chemical Engineering
Master of Science and Doctor of Philosophy

Join a small, vibrant campus on Florida's Space Coast to reach your full academic and professional potential. Florida Tech, the only independent scientific and technological university in the Southeast, has grown to become a university of international standing.

Graduate Student Assistantships/
Tuition Remission available

Faculty

P.A. Jennings, Ph.D.
D.R. Mason, Ph.D.
M.E. Pozo de Fernandez, Ph.D.
M.R. Shaffer, Ph.D.
M.M. Tomadakis, Ph.D.
J.E. Whitlow, Ph.D

Research Partners

• NASA/Kennedy Space Center
• Florida Solar Energy Center
• Energy Partners
• Florida Institute of Phosphate Research
• Florida Department of Energy
• Harris Semiconductor

Research Interests

• Spacecraft Technology
• Semiconductor Manufacturing
• Alternative Energy Sources
• Materials Science
• Environmental Engineering
• Expert Systems

For more information, contact

Florida Institute of Technology
Chemical Engineering Program
College of Engineering
Division of Engineering Sciences
150 West University Boulevard
Melbourne, Florida 32901-6975
(407) 674-8068
Chemical Engineering
The Faculty and Their Research

Home of the 1996 Olympic Village

Georgia Institute of Technology

A.S. Abhiraman
Polymer science and engineering

Pradeep K. Agrawal
Heterogeneous catalysis, surface chemistry, reaction kinetics

Yaman Arkun
Process design and control, spouted-bed reactors

Sue Ann Bidstrup-Allen
Microelectronics processing, thin film science and technology, plasma processes

Charles A. Eckert
Molecular thermodynamics, chemical kinetics, separations

William R. Ernst
Reactor design, catalysis

Larry J. Forney
Mechanics of aerosols, buoyant plumes and jets

Dennis W. Hess
Microelectronics systems, interfacial phenomena, fine-particle technology

Paul A. Kohl
Photochemical processing, chemical vapor deposition

Charles L. Liotta
Synthesis and properties of polymeric materials, computer modeling of chemical processes

Peter J. Ludovice
Molecular modeling of polymeric materials

Michael J. Matteson
Aerocolloidal systems, interfacial phenomena, fine-particle technology

John D. Muzzy
Polymer engineering, energy conservation, economics

Robert M. Nerem
Biomechanics, mammalian cell structures

Gary W. Pochleitn
Emulsion polymerization, latex technology

Jeffrey F. Morris
Fluid mechanics, two phase flows, complex fluids

Ronald W. Rousseau
Mass transfer, extraction, mixing, non-Newtonian flow

Ronnie S. Roberts
Separation processes, crystallization

Paul A. Kohl
Optimal process design and scheduling

Mary E. Rezac
Membrane separations, mass transfer

A. H. Peter Skelland
Biochemical engineering, mass transfer, reactor design

Jude T. Sommerfeld
Process design and simulation

Arnold F. Stancell
Membranes, polymers, process economics

F. Joseph Schork
Reactor engineering, process control, polymerization, reactor dynamics

Mark G. White
Catalysis, kinetics, reactor design

Timothy M. Wick
Biochemical engineering, cell-cell interactions, biofluid dynamics

Jack Winnick
Electrochemical engineering, thermodynamics, air pollution control

Amyn S. Teja
Thermodynamic and transport properties, phase equilibria, supercritical extraction

Ajit P. Yoganathan
Process synthesis and simulation, chemical separation, waste management, resource recovery

For more information, contact: Dr. Ronald Rousseau, Chair
School of Chemical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0100
What do graduate students say about the University of Houston Department of Chemical Engineering?

"It's great!"

"Houston is a university on the move. The chemical engineering department is ranked among the top ten schools, and you can work in the specialty of your choice. The choice of advisor is yours, too, and you're given enough time to make the right decision. You can see your advisor almost anytime you want because the student-to-teacher ratio is low."

If you'd like to be part of this team, let us hear from you!

**AREAS OF RESEARCH STRENGTH**

- Biochemical & Tissue Engineering
- Reaction Engineering & Catalysis
- Electronic and Ceramic Materials
- Environmental Remediation
- Multiphase Flow
- Nonlinear Dynamics
- Polymer & Macromolecular Systems
- Process Control and Optimization

**FACULTY**

<table>
<thead>
<tr>
<th>Faculty Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neal Amundson</td>
</tr>
<tr>
<td>Vemuri Balakotaiah</td>
</tr>
<tr>
<td>Demetre Economou</td>
</tr>
<tr>
<td>Ernest Henley</td>
</tr>
<tr>
<td>John Killough</td>
</tr>
<tr>
<td>Ramanan Krishnamoorti</td>
</tr>
<tr>
<td>Dan Luss</td>
</tr>
<tr>
<td>Kishore Mohanty</td>
</tr>
<tr>
<td>Mike Nikolaou</td>
</tr>
<tr>
<td>Richard Pollard</td>
</tr>
<tr>
<td>William Prengle</td>
</tr>
<tr>
<td>Jim Richardson</td>
</tr>
<tr>
<td>Frank Tiller</td>
</tr>
<tr>
<td>Richard Willson</td>
</tr>
<tr>
<td>Frank Worley</td>
</tr>
</tbody>
</table>

For an application, write:
Graduate Admissions Coordinator, Dept. of Chemical Engineering, University of Houston, 4800 Calhoun, Houston, TX 77204-4792, or call 713/743-4311.

The University is an Equal Opportunity/Affirmative Action Institution
Chemical Engineering at Howard University

Where modern instructional and research laboratories, together with computing facilities, support both student and faculty research pursuits on an eighty-nine acre main campus three miles north of the heart of Washington, DC.

Faculty and Research Interests

Mobolaji E. Aluko, Professor and Chair
PhD, University of California, Santa Barbara
Reactor modeling • crystallization • microelectronic and ceramic materials processing • process control • reaction engineering analysis

Joseph N. Cannon, Professor • PhD, University of Colorado
Transport phenomena in environmental systems • computational fluid mechanics • heat transfer

Ramesh C. Chawla, Professor • PhD, Wayne State University
Mass transfer and kinetics in environmental systems • bioremediation • incineration • air and water pollution control

William E. Collins, Assistant Professor • PhD, University of Wisconsin-Madison
Polymer deformation, rheology, and surface science • biomaterials • bioseparations • materials science

M. Gopala Rao, Professor • PhD, University of Washington, Seattle
Adsorption and ion exchange • process energy systems • radioactive waste management • remediation of contaminated soils and groundwater

John P. Tharakan, Associate Professor • PhD University of California, San Diego
Bioprocess engineering • protein separations • biological hazardous waste treatment • bio-environmental engineering

Robert J. Lutz, Visiting Professor • PhD, University of Pennsylvania
Biomedical engineering • hemodynamics • drug delivery • pharmacokinetics

Herbert M. Katz, Professor Emeritus • PhD, University of Cincinnati
Environmental engineering

For further information and applications, write to

M.S. Program

Director, Graduate Studies • Chemical Engineering Department
Howard University • Washington, DC 20059
Phone 202-806-6624 Fax 202-806-4635

Fall 1997
FACULTY

John H. Kiefer, Professor and Head
Ph.D., Cornell University, 1961
E-Mail: Kiefer@UIC.EDU

Kenneth Brezinsky, Professor
Ph.D., City University of New York, 1978
E-Mail: Kenbrez@UIC.EDU

G. Ali Mansoori, Professor
Ph.D., University of Oklahoma, 1969
E-Mail: Mansoori@UIC.EDU

Sohail Murad, Professor
Ph.D., Cornell University, 1979
E-Mail: Murad@UIC.EDU

Ludwig C. Nitsche, Associate Professor
Ph.D., Massachusetts Institute of Technology, 1989
E-Mail: LCN@UIC.EDU

John Regalbuto, Associate Professor
Ph.D., University of Notre Dame, 1986
E-Mail: JRR@UIC.EDU

Héctor R. Reyes, Assistant Professor
Ph.D., University of Wisconsin, Madison, 1991
E-Mail: HReyes@UIC.EDU

Satish C. Saxena, Professor
Ph.D., Calcutta University, 1956
E-Mail: Saxena@UIC.EDU

Stephen Szepe, Associate Professor
Ph.D., Illinois Institute of Technology, 1966
E-Mail: SSzepe@UIC.EDU

Christos Takoudis, Professor
Ph.D., University of Minnesota, 1982
E-Mail: Takoudis@UIC.EDU

Raffi M. Turian, Professor
Ph.D., University of Wisconsin, 1964
E-Mail: Turian@UIC.EDU

RESEARCH AREAS

Transport Phenomena: Transport properties of fluids, slurry transport, multiphase fluid flow and heat transfer, fixed and fluidized bed combustion, indirect coal liquefaction, porous media.

Thermodynamics: Molecular simulation and statistical mechanics of liquid mixtures. Superficial fluid extraction/retrograde condensation, asphaltene characterization. Reverse osmosis separations.


Materials: Microelectronic materials and processing, heteroepitaxy in group IV materials, and in situ surface spectroscopies at interfaces. Combustion synthesis of ceramics and synthesis in supercritical fluids.

For more information, write to
Director of Graduate Studies • Department of Chemical Engineering
University of Illinois at Chicago • 810 S. Clinton • Chicago, IL 60607-7000 • (312) 996-3424 • Fax (312) 996-0808
URL: http://www.uic.edu/depts/chme/

Chemical Engineering Education
Chemical Engineering at the

University of Illinois

at Urbana-Champaign

The combination of distinguished faculty, outstanding facilities and a diversity of research interests results in exceptional opportunities for graduate education.

The chemical engineering department offers graduate programs leading to the M.S. and Ph.D. degrees.

<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Research Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Richard C. Alkire</td>
<td>Electrochemical Engineering</td>
</tr>
<tr>
<td>Richard D. Braatz</td>
<td>Advanced Process Control</td>
</tr>
<tr>
<td>Vinay K. Gupta</td>
<td>Interfacial Phenomena: Structure and Dynamics in Thin Films</td>
</tr>
<tr>
<td>Jonathan J. L. Higdon</td>
<td>Fluid Mechanics and Transport Phenomena</td>
</tr>
<tr>
<td>Deborah E. Leckband</td>
<td>Biomolecular Recognition</td>
</tr>
<tr>
<td>Richard I. Masel</td>
<td>Fundamental Studies of Catalytic Processes and Semiconductor Growth</td>
</tr>
<tr>
<td>Anthony J. McHugh</td>
<td>Polymer Science and Engineering</td>
</tr>
<tr>
<td>Nikolaos V. Sahinidis</td>
<td>Optimization and Process Systems Engineering</td>
</tr>
<tr>
<td>William R. Schowalter</td>
<td>Mechanics of Complex Fluids</td>
</tr>
<tr>
<td>Edmund G. Seebauer</td>
<td>Laser Studies of Semiconductor Growth</td>
</tr>
<tr>
<td>K. Dane Wittrup</td>
<td>Biochemical Engineering</td>
</tr>
<tr>
<td>Charles F. Zukoski</td>
<td>Colloid and Interfacial Science</td>
</tr>
</tbody>
</table>

For information and application forms write:

Department of Chemical Engineering
University of Illinois at Urbana-Champaign
Box C-3 Roger Adams Lab
600 S. Mathews Ave.
Urbana, Illinois 61801-3792
http://www.scs.uiuc.edu/chem_eng/
GRADUATE STUDY IN CHEMICAL AND ENVIRONMENTAL ENGINEERING AT
Illinois Institute of Technology

THE UNIVERSITY
◆ Private, coeducational and research university ◆ 2000 undergraduate students ◆ 3100 graduate students ◆ Campus recognized as an architectural landmark ◆ Three miles from downtown Chicago and one mile west of Lake Michigan

THE DEPARTMENT
◆ Merger of chemical and environmental engineering departments created state-of-the-art, interdisciplinary research and education programs ◆ Approximately 65 full-time and 200 part-time graduate students ◆ M.S., Professional Master, and Ph.D. degrees in chemical and environmental engineering ◆ Fellowships and assistantships available to outstanding students

APPLICATIONS
Graduate Admissions Coordinator
Chemical and Environmental Engineering Department
Illinois Institute of Technology
10 W. 33rd Street
Chicago, IL 60616-3793
Phone: 312-567-3533; Fax: 312-567-8874
http://www.chee.iit.edu/
e-mail: chee@charlie.cns.iit.edu

FACULTY AND RESEARCH AREAS

Chairman: Hamid Arastoopour
Chemical Engineering Program
Associate Chairman: Ali Cinar

Hamid Arastoopour; computational multiphase flow, fluidization, material processing, particle technology, fluid-particle flow
Richard L. Beissinger; transport processes in biological systems, biomedical engineering, bioreheology
Barry Bernstein; computational fluid mechanics, material properties, polymer rheology
Ali Cinar; chemical and food process control, nonlinear input-output modeling, statistical process monitoring
Dimitri Gidaspow; hydrodynamics of fluidization using kinetic theory, gas-solid transport
Henry R. Linden; fossil fuel technologies, energy and resource economics, energy and environmental policy
Satish Parulekar; biochemical engineering, chemical reaction engineering
Jay D. Schieber; kinetic theory, polymer rheology predictions, transport phenomena, non-Newtonian fluid mechanics
J. Robert Selman; applied electrochemistry and electrochemical engineering, battery and fuel cell design
Eugene S. Smotkin; FTIR spectroscopy of electrode surfaces, electrochemical mass spectroscopy, fuel cells
Fouad A. Teymour; polymer reaction engineering, mathematical modeling, nonlinear dynamics
David C. Venerus; polymer rheology and processing, transport phenomena in polymeric systems
Darsh T. Wasan; thin liquid films; interfacial rheology; foams, emulsion and dispersion, environmental technologies

Environmental Engineering Program
Associate Chairman: Thomas M. Holsen

Paul R. Anderson; precipitation kinetics, evaluation of oxide adsorbents for water and wastewater treatment
H. Ted Chang; biological processes, hazardous waste remediation, groundwater aquifer remediation
Thomas M. Holsen; environmental chemistry, hazardous and industrial waste treatment
Nasrin R. Khallili; evaluation of adsorption capacity of solid adsorbents in waste control, industrial waste management strategies
Demetrios J. Moschandreass; ambient and indoor air pollution, statistical analysis, environmental impact assessment
Kenneth E. Noll; air resources engineering, air pollution meteorology, hazardous waste treatment
Krishna R. Fagilla; water and wastewater engineering, environmental microbiology, soil remediation, sludge treatment

Adjunct and Research Faculty

Nader Aderangi ◆ V.M. Balasubramanian ◆ Michael Caracotsios
Ellis Fields ◆ Ted Knowlton ◆ Harold Lindahl ◆ Alex Nikolov
Robert Peters ◆ Allen Tulis ◆ Hwa-Chi Wang
Graduate program for M.S. and Ph.D. degrees in Chemical and Biochemical Engineering

FACULTY

Jonathan S. Dordick (Chair)  
MIT 1986  
Biocatalysis and bioprocessing/Polymmer chemistry

Audrey Butler  
(Adjunct)  
U. of Iowa 1989  
Global change/Supercomputing/Air pollution modeling

Greg Carmichael  
U. of Kentucky 1979  
Chemical precipitation processes

Ravi Datta  
UCSB 1981  
Reaction engineering/Catalyst engineering

Stephen K. Hunter  
(Adjunct)  
U. of Utah 1989  
Bioprocessing/Microencapsulation technologies

Yuri Khmelnitsky  
(Adjunct)  
Moscow State U. 1982  
Chemical enzymology and biocatalysis

Robert Linhardt  
Johns Hopkins 1979  
Biopolymers and pharmaceutical applications

David Murhammer  
U. of Houston 1989  
Insect cell culture/Bioreactor monitoring/Prostate cancer cell culture

Tonya L. Peeples  
Johns Hopkins 1994  
Bioremediation/Extremophile physiology and biocatalysis

David Rethwisch  
U. of Wisconsin 1985  
Membrane science/Polymmer science

V.G.J. Rodgers  
Washington U. 1989  
Transport phenomena in bioseparations/Membrane separations

John M. Wiencek  
Case Western Reserve 1989  
Protein crystallization/Surfactant technology

For information and application:  
The University of Iowa  
Graduate Admissions  
Chemical and Biochemical Engineering  
125 Chemistry Building  
Iowa City IA 52242-1219  
1-800-553-IOWA  
(1-800-553-4692)  
chemeng@iarc.chemeng.uiowa.edu
Biochemical and Biomedical Engineering

Charles E. Glatz, Ph.D.
Wisconsin

Carole A. Heath, Ph.D.
R.P.I.

Richard C. Seagrave, Ph.D.
Iowa State

Peter J. Reilly, Ph.D.
Pennsylvania

Catalysis and Reaction Engineering

L. K. Doraiswamy, Ph.D.
Wisconsin

Glenn L. Schrader, Ph.D.
Wisconsin

Chemical Engineering

Energy and Environment

Thomas D. Wheelock, Ph.D.
Iowa State

Robert C. Brown, Ph.D.
Michigan State

Materials and Crystallization

Kurt R. Hebert, Ph.D.
Illinois

Maurice A. Larson, Ph.D.
Iowa State

Gordon R. Youngquist, Ph.D.
Illinois

Surya Mallapragada, Ph.D.
Purdue

Process Design and Control

Dean L. Ulrichson, Ph.D.
Iowa State

Derrick K. Rollins, Ph.D.
Ohio State

Transport and Thermodynamics

James C. Hill, Ph.D.
Washington

Kenneth R. Jolls, Ph.D.
Illinois

R. Dennis Vigil, Ph.D.
Michigan

Chris Baldwin, Ph.D.
Cambridge
Graduate Study and Research in Chemical Engineering at Johns Hopkins

The Johns Hopkins University's Department of Chemical Engineering, established in 1956, features a low student-to-faculty ratio that fosters a highly collaborative research experience. The faculty are internationally known for their contributions in the traditional areas of chemical engineering research, such as thermodynamics, fluid dynamics, and rheology, and at the forefront of emerging technologies, such as membrane-based separation processes, recombinant DNA technology, tissue engineering, and molecular/cellular biomedical engineering.

<table>
<thead>
<tr>
<th>Membrane Science</th>
<th>Surfactant/Supercritical Fluid Phase Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorption and Diffusion in Polymers</td>
<td>Computational Molecular Thermodynamics</td>
</tr>
<tr>
<td>Polymeric Separation Media</td>
<td>Polymer/Protein Thermodynamics</td>
</tr>
<tr>
<td>Timothy A. Barbari, PhD</td>
<td>Michael E. Paulaitis, PhD</td>
</tr>
<tr>
<td>University of Texas, Austin</td>
<td>University of Illinois</td>
</tr>
<tr>
<td>Insect Cell Culture</td>
<td>Interfacial Phenomena</td>
</tr>
<tr>
<td>Recombinant DNA Technology</td>
<td>Surfactant Transport Kinetics</td>
</tr>
<tr>
<td>Protein Folding and Aggregation</td>
<td>Marangoni Effects</td>
</tr>
<tr>
<td>Michael J. Betenbaugh, PhD</td>
<td>Kathleen J. Stebe, PhD</td>
</tr>
<tr>
<td>University of Delaware</td>
<td>The City University of New York</td>
</tr>
<tr>
<td>Equations of State</td>
<td>Complex Fluids</td>
</tr>
<tr>
<td>Statistical Thermodynamics</td>
<td>Light, Neutron, and X-ray Scattering</td>
</tr>
<tr>
<td>Solvent Replacement</td>
<td>Polymer Interfaces</td>
</tr>
<tr>
<td>Marc D. Donohue, PhD</td>
<td>John H. van Zanten, PhD</td>
</tr>
<tr>
<td>University of California, Berkeley</td>
<td>University of California, Los Angeles</td>
</tr>
<tr>
<td>Nucleation</td>
<td>Phase Transitions and Critical Phenomena</td>
</tr>
<tr>
<td>Crystallization</td>
<td>Polymer Systems Far from Equilibrium</td>
</tr>
<tr>
<td>Flame Generation of Ceramic Powders</td>
<td>Particle-Tracking Microrheology</td>
</tr>
<tr>
<td>Joseph L. Katz, PhD</td>
<td>Denis Wirtz, PhD</td>
</tr>
<tr>
<td>University of Chicago</td>
<td>Stanford University</td>
</tr>
<tr>
<td>Fluid Mechanics in Medical Applications</td>
<td></td>
</tr>
<tr>
<td>Vascular and Cellular Biology</td>
<td>For further information contact:</td>
</tr>
<tr>
<td>Thrombosis, Inflammation, Cancer Metastasis</td>
<td></td>
</tr>
<tr>
<td>Konstantinos Konstantopoulos, PhD</td>
<td>Johns Hopkins University</td>
</tr>
<tr>
<td>Rice University</td>
<td>Whiting School of Engineering</td>
</tr>
<tr>
<td>High-Pressure Thermodynamics</td>
<td>Department of Chemical Engineering</td>
</tr>
<tr>
<td>Polymer Solution Thermodynamics</td>
<td>5400 N. Charles Street</td>
</tr>
<tr>
<td>Supercritical Solvent Extraction</td>
<td>Baltimore, MD 21218-2681</td>
</tr>
<tr>
<td>Mark A. McHugh, PhD</td>
<td>410-516-5455 / <a href="mailto:che@jhu.edu">che@jhu.edu</a></td>
</tr>
<tr>
<td>University of Delaware</td>
<td><a href="http://www.jhu.edu/~cheme/ChemE.html">http://www.jhu.edu/~cheme/ChemE.html</a></td>
</tr>
</tbody>
</table>
The University of Kansas is the largest and most comprehensive university in Kansas. It has an enrollment of more than 28,000 and almost 2,000 faculty members. KU offers more than 100 bachelors', nearly ninety masters', and more than fifty doctoral programs.

The main campus is in Lawrence, Kansas, with other campuses in Kansas City, Wichita, Topeka, and Overland Park, Kansas.

GRADUATE PROGRAMS

- M.S. degree with a thesis requirement in both chemical and petroleum engineering
- Ph.D. degree characterized by moderate and flexible course requirements and a strong research emphasis
- Typical completion times are 16-18 months for a M.S. degree and 4 1/2 years for a Ph.D. degree (from B.S.)

FINANCIAL AID

Financial aid is available in the form of fellowships and research and teaching assistantships ($13,000 to $16,000 a year)

For more information and application material, write or call

The Graduate Adviser
Department of Chemical and Petroleum Engineering
4006 Learned Hall
The University of Kansas
Lawrence, KS 66045-2223
http://www.engr.ukans.edu/cpe-grad/
M.S. and Ph.D. Programs
- Chemical Engineering
- Interdisciplinary Areas of Systems Engineering
- Food Science
- Environmental Engineering

Financial Aid Available
Up to $17,000 Per Year

For More Information Write To
Professor J. H. Edgar
Durland Hall
Kansas State University
Manhattan, KS 66506
or visit our web site at
http://www.engage.ksu.edu/CHEDEP/DEPT/home.html

Areas of Study and Research
- Transport Phenomena
- Computational Fluid Dynamics
- Coal and Biomass Conversion
- Molecular Thermodynamics
- Biochemical Engineering
- Process Dynamics and Control
- Chemical Reaction Engineering
- Intelligent Processing of Materials
- Chemical Vapor Deposition of Electronic Materials
- Process System Engineering and Artificial Intelligence
- Environmental Pollution Control
- Computer Simulation and Interfacial Studies
- Hazardous Waste Treatment
The Program:

The graduate program in Chemical Engineering at the University of Kentucky offers advanced studies leading to the M.S. and Ph.D. degrees. Faculty research interests span a range of important and evolving technical areas, and include interdisciplinary efforts in a number of fields. Areas of research emphasis include:

- Aerosols
- Biocellular engineering
- Environmental engineering
- Fuel science
- Membranes
- Polymer engineering
- Supercritical fluids processing
- Transport phenomena

The department currently has 50 graduate students, over half of whom are pursuing the Ph.D.

The Faculty:

K. Anderson; Carnegie-Mellon
D. Bhattacharyya; Illinois Institute of Technology
F. Derbyshire; Imperial College
E. Gruulke; Ohio State University
C. Hamrin; Northwestern
D. Kalika; University of California, Berkeley
R. Kermode; Northwestern
B. Knutson; Georgia Institute of Technology
A. Ray; Clarkson
J.T. Schrodt; University of Louisville
T. Tsang; University of Texas

Contact Us!!

E-mail CMEG@engr.uky.edu
Web http://www.engr.uky.edu

or

Director of Graduate Studies
177 Anderson Hall
Lexington, KY 40506-0046
606-257-4956
Faculty and Research Areas

Abdellatif Ait-Kadi
(Ph.D. École Polytechnique de Montréal)
aitkadi@gch.ulaval.ca
(418) 656-5222
- rheology
- processing
- rheological modelling

Mosto Mostapha Bousmina
(Ph.D. École des Hauts Polymères, Strasbourg)
bousmina@gch.ulaval.ca
(418) 656-2769
- rheology and modelling
- polymer blends and alloys
- polymer physics and engineering

Alain Garnier
(Ph.D. École Polytechnique de Montréal)
alain.garnier@gch.ulaval.ca
(418) 656-3106
- biotechnology
- animal cell culture
- viral vectors and vaccines production

Suzanne Giasson
(Ph.D. Western Ontario and IFP, Paris)
sgiasson@gch.ulaval.ca
(418) 656-3774
- colloids: polymers, surfactants
- interfacial phenomena
- surface forces

Bernard Grandjean
(Ph.D. École Polytechnique de Montréal)
grandjean@gch.ulaval.ca
(418) 656-2659
- catalytic membrane reactors
- neural network modelling
- industrial wastewater treatment

Serge Kallaguine
(D. ing. IGC Toulouse)
kallaguine@gch.ulaval.ca
(418) 656-2708
- zeolites and carbon blacks
- catalytic membranes
- industrial catalysis

René Lacroix
(Ph.D. Univ. Laval)
lacroix@gch.ulaval.ca
(418) 656-3584
- numerical simulation of polymer processing
- numerical simulation of thermo-electrical problem
- finite element method

Faiçal Larachi
(Ph.D. INPL, Nancy)
flarachi@gch.ulaval.ca
(418) 656-3566
- multiphase reactors
- wet oxidation
- flow instrumentation

Anh LeDuy
(Ph.D. Western Ontario)
leduy@gch.ulaval.ca
(418) 656-2634
- biochemical and microbial processes
- bio kinetics

Denis Rodrigue
(Ph.D. Université de Sherbrooke)
drodrigue@gch.ulaval.ca
(418) 656-2903
- transport phenomena
- rheology
- oriented polymers

Christian Roy
(Ph.D. Sherbrooke)
croy@gch.ulaval.ca
(418) 656-7406
- pollution prevention
- solid wastes
- vacuum pyrolysis

Abdelhamid Sayari
(Ph.D. Tunis/Lyon)
sayari@gch.ulaval.ca
(418) 656-3563
- heterogeneous catalysis
- zeolites and molecular sieves
- superacid catalysts

Jules Thibault
(Ph.D. McMaster)
jules.thibault@gch.ulaval.ca
(418) 656-2443
- process identification and control
- bioreactor engineering
- neural network modelling

Additional information and Applications may be obtained to:
Graduate Program Coordinator
Department of Chemical Engineering
Université Laval
Québec Canada G1K 7P4
info.grad@gch.ulaval.ca
www.gch.ulaval.ca
tél. (418) 656-2131 poste 8073
télécop. (418) 656-5993
Synergistic, interdisciplinary research in...

- Biochemical Engineering
- Catalytic Science & Reaction Engineering
- Environmental Engineering
- Interfacial Transport
- Materials Synthesis Characterization & Processing
- Microelectronics Processing
- Polymer Science & Engineering
- Process Modeling & Control
- Thermodynamic Properties
- Two-Phase Flow & Heat Transfer

... leading to M.S. and Ph.D. degrees in chemical engineering and polymer science and engineering

Highly attractive financial aid packages, which provide tuition and stipend, are available.

Living in Bethlehem, PA allows easy access to cultural and recreational opportunities in the New York-Philadelphia area.

Additional information and applications may be obtained by writing to:

Dr. Maria M. Santore, Chairman • Graduate Admissions Committee
Department of Chemical Engineering • Lehigh University • 111 Research Drive • Iacocca Hall • Bethlehem, PA 18015
THE CITY

Baton Rouge is the state capital 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. Baton Rouge is one of the nation's busiest ports and the city's economy rests heavily on the chemical, oil, plastics, and agricultural industries. The great outdoors provide excellent recreational activities year-round, especially fishing, hunting, and water sports. The proximity of New Orleans provides for superb nightlife, especially during Mardi Gras. The city is also only two hours away from the Mississippi Gulf Coast, and four hours from either Gulf Shores or Houston.

THE DEPARTMENT

- M.S. and Ph.D. Programs
- Approximately 60 Graduate Students
- Average research funding more than $2 million per year

DEPARTMENTAL FACILITIES

- Departmental computing—IBM 9370 and RS 6000's with LAN and more than 80 PCs
- Extensive laboratory facilities, especially in reaction and environmental engineering, transport phenomena and separations, polymer, textile and materials processing, biochemical engineering, thermodynamics

FACULTY

J.R. COLLIER (Ph.D., Case Western University)
Polymer and Textile Processing

A.B. CORRIPIO (Ph.D., Louisiana State University)
Control, Simulation, Computer-Aided Design

K.M. DOOLEY (Ph.D., University of Delaware)
Heterogeneous Catalysis, High-Pressure Separations

G.L. GRIFFIN (Ph.D., Princeton University)
Electronic Materials, Surface Chemistry, CVD

D.P. HARRISON (Ph.D., University of Texas)
Fluid-Solid Reactions, Hazardous Waste Treatment

M.A. HENSON (Ph.D., UC Santa Barbara)
Nonlinear Process Control, Neural Networks

M.A. HJORTSØ (Ph.D., University of Houston)
Biochemical Reaction Engineering, Applied Math

F.C. KNOPF (Ph.D., Purdue University)
Supercritical Fluid Extraction, Ultrafast Kinetics

R.W. PIKE (Ph.D., Georgia Institute of Technology)
Fluid Dynamics, Reaction Engineering, Optimization

E.J. PODLAHA (Ph.D., Columbia University)
Electrical Phenomena, Alloy and Composite Materials

G.L. PRICE (Ph.D., Rice University)
Heterogeneous Catalysis, Zeolites

M. RADOSZ (Ph.D., University of Cracow)
Thermodynamics, Polymer Physical Chemistry

D.D. REIBLE (Ph.D., California Institute of Technology)
Environmental Transport, Transport Modeling

A.M. STERLING (Ph.D., University of Washington)
Transport Phenomena, Combustion

L.J. THIBODEAUX (Ph.D., Louisiana State University)
Chemodynamics, Hazardous Waste Transport

K.E. THOMPSON (Ph.D., University of Michigan)
Transport and Reaction in Porous Media

K.T. VALSARAJ (Ph.D., Vanderbilt University)
Environmental Transport, Separations

D.M. WETZEL (Ph.D., University of Delaware)
Hazardous Waste Treatment, Drying

FINANCIAL AID

- Assistantships at $14,400 - $18,200, with waiver of out-of-state tuition
- Dean's Fellowships at $17,000 per year with no tuition
The University

The spacious campus is situated on 1,200 acres overlooking the Penobscot and Stillwater Rivers. Present enrollment of 12,000 offers the diversity of a large school, while preserving close personal contact between peers and faculty. The University’s Maine Center for the Arts, the Hauck Auditorium, and Pavilion Theatre provide many cultural opportunities, in addition to those in the nearby city of Bangor. Less than an hour away from campus are the beautiful Maine Coast and Acadia National park, alpine and cross-country ski resorts, and northern wilderness areas of Baxter State Park and Mount Katahdin.

Faculty and Research Interests

DOUGLAS BOUSFIELD Ph.D. (U.C.Berkeley)
Fluid Mechanics, Rheology, Coating Processes, Particle Motion Modeling

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

JOSEPH M. GENCPh.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)
Environmental Science, Waste Management Technology

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

PIERRE LEPOUTRE Ph.D. (North Carolina State University)
Surface Physics and Chemistry, Materials Science, Adhesion Phenomena

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

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

DOUGLAS M. RUTHVEN Ph.D., Sc.D. (Cambridge)
Chair
Fundamentals of Adsorption and Adsorption Processes

EDWARD V. THOMPSON Ph.D., (Polytechnic Institute of Brooklyn)
Thermal & Mechanical Properties of Polymers, Papermaking and Fiber Physics, Recycle Paper

Programs and Financial Support

Industrial fellowships, university fellowships, research assistantships and teaching assistantships are available. Various research programs such as paper surface science and recycled fiber have industrial advisory boards. These boards provide students contact with industry researchers. Facilities include modern well-equipped laboratories and a pulp and paper pilot plant.

Call Collect or Write

Doug Bousfield
Department of Chemical Engineering
Jenness Hall, Box B
University of Maine
Orono, Maine
04469-5737
(207) 581-2300

e-mail: bousfd@maine.maine.edu • web site: http://www.umecheme.maine.edu
This well-established graduate program emphasizes the application of basic principles to the solution of process engineering problems.

Financial aid is available, including industrial fellowships in a one-year program involving participation of the following companies:

- ABB Lummus Crest, Inc.
- Air Products and Chemicals, Inc.
- Consolidated Edison Co.
- Metcalf & Eddy, Inc.
- Mobile Oil Corporation
- Pfizer, Inc.

For brochure and application form, write to

Director
Chemical Engineering Department
Manhattan College
Riverdale, NY 10471
EMPHASIS
The Department of Chemical and Biochemical Engineering at UMBC offers graduate programs leading to M.S. and Ph.D. degrees in Chemical Engineering. Our research is heavily focused in biochemical and bioprocess engineering and covers a wide range of areas including fermentation, cell culture, downstream processing, drug delivery, protein engineering and protein stability. Unique programs in the regulatory-engineering interface of bioprocessing are offered as well.

FACILITIES
The Department offers state-of-the-art facilities for faculty and graduate student research. These modern facilities have been developed primarily in the last six years and comprise 6,000 square feet of laboratory space in the Technology Research Center plus 7,000 square feet of departmental laboratories in the new Engineering and Computer Science building, a $26 million facility opened in the Fall of 1992.

LOCATION
UMBC is located in the Baltimore-Washington corridor and within easy access to both metropolitan areas. A number of government research facilities such as NIH, FDA, USDA, NSA and a large number of biotechnology companies are located nearby and provide excellent opportunities for research interactions.

FOR FURTHER INFORMATION
CONTACT:
Graduate Program Coordinator
Department of Chemical and Biochemical Engineering
University of Maryland Baltimore County
5401 Wilkens Avenue
Baltimore, Maryland 21228-5398
Phone: (410) 455-3400
FAX: (410) 455-1049

FACULTY
D. F. Bruley, Ph.D. Tennessee
Biodownstream processing and processes in the microcirculation; Process simulation and control.

D. D. Frey, Ph.D. California-Berkeley
Chromatographic separations; Electrophoresis.

A. Gomezplata, Ph.D.* Rensselaer
Heterogeneous flow systems; Simultaneous mass transfer and chemical reactions.

K. A. Kang, Ph.D. California-Davis
Immunocompany chromatography; Characterization and imaging of biological systems; Transport phenomena.

J. A. Lumpkin, Ph.D. Pennsylvania
Protein oxidation; Kinetics of enzymatic reactions; Analytical chemi- and bioluminescence.

A. R. Moreira, Ph.D. Pennsylvania
rDNA fermentation; Regulatory issues; Scale-up; Downstream processing.

G. F. Payne, Ph.D.** Michigan
Plant cell tissue culture; Streptomyces bioprocessing; Adsorptive separations; Toxic waste treatment.

G. Rao, Ph.D.** Drexel
Animal cell culture; Oxygen toxicity; Biosensing.

J. M. Ross, Ph.D. Pennsylvania
Cell adhesion; Biofilm formation.

M. R. Sierks, Ph.D. Iowa State
Protein engineering; Site-directed mutagenesis; Catalytic antibodies.

D. I.C. Wang, Ph.D.† Pennsylvania
Bioreactors; Bioinstrumentation; Protein refolding.

* Emeritus
** Joint appointment with the University of Maryland Biotechnology Institute
† Adjunct Professor
Faculty and Research Areas

Raymond A. Adomaitis (ITT) • Systems modeling and simulation methodologies; RTCVD model reduction; flow instability control
Mikhail A. Anisimov (Moscow) • Critical phenomena and phase transitions in fluids and fluid mixtures
William E. Bentley (Colorado-Boulder) • Biochemical engineering, metabolic engineering, applications of molecular biology
Richard V. Calabrese (Massachusetts) • Multiphase flow, turbulence and mixing
Kyu Yong Choi (Wisconsin) • Polymer reaction engineering
Larry L. Gasner (MIT) • Environmental engineering
James W. Gentry (Texas-Austin) • Aerosol science and engineering
Sandra C. Greer (Chicago) • Physical chemistry, polymer science
Michael T. Harris (Tennessee) • Nanoparticle technology
Peter Kofinas (MIT) • Polymer science and engineering
Thomas J. McAvoy (Princeton) • Process control, neural network applications
Athanassios Z. Panagiotopoulos (MIT) • Thermodynamics and molecular simulations
Thomas M. Regan (Tulane) • Teaching/learning pedagogy and delivery systems
Jan V. Sengers (U. Amsterdam) • Critical phenomena, thermophysical properties of fluids and fluid mixtures
Theodore G. Smith (Washington U.) • Polymer processing, polymer blends and characterization
Nam Sun Wang (Caltech) • Biochemical engineering
William A. Weigand (ITT) • Biochemical engineering, bioprocess control and optimization
Evanghelos Zafiriou (Caltech) • Process control, identification and optimization

Location: The University of Maryland at College Park is located approximately 10 miles from the heart of the nation, Washington, D.C., and 25 miles from Baltimore.
Come to Chemical Engineering at the University of Massachusetts Amherst.

Amherst is a small New England town in Western Massachusetts. Set amid farmland and rolling hills, the area offers pleasant living conditions and extensive recreational facilities, and urban pleasures are easily accessible.

See us on our Web page http://www.ecs.umass.edu/che/

Faculty
M.F. Malone (Massachusetts), Head
W.C. Conner, Jr. (Johns Hopkins)
M.F. Doherty (Cambridge)
J.M. Douglas (Delaware)
V. Haensel (Northwestern)
R.L. Laurence (Northwestern)
P.A. Monson (London)
K.M. Ng (Houston)
M. Tsapatsis (Caltech)
J.W. van Egmond (Stanford)
D.G. Vlachos (Minnesota)
J.J. Watkins (Massachusetts)
P.R. Westmoreland (MIT)
H.H. Winter (Stuttgart)
Z.Q. Zheng (Caltech)

Current Areas of MS and PhD Research
• Robust process control
• Azeotropic, extractive, and reactive distillation
• Crystallization and design of solids processing
• Polymer processing and reactor engineering
• Catalyst and catalytic reactor development
• Noncatalytic gas and gas-solid kinetics:
  Combustion, PECVD, and polymer pyrolysis
• Fluid mechanics and polymer rheology
• Statistical mechanics and phase behavior
• Applied ab initio computational chemistry

Financial Support
All students are awarded full financial aid at a nationally competitive rate.

For application forms and further information on fellowships and assistantships, academic and research programs, and student housing, write:
Graduate Program Director
Department of Chemical Engineering
159 Goessmann Laboratory, Box 33110
University of Massachusetts
Amherst, MA 01003-3110

The University of Massachusetts Amherst prohibits discrimination on the basis of race, color, religion, creed, sex, sexual orientation, age, marital status, national origin, disability or handicap, or veteran status, in any aspect of the admission or treatment of students or in employment.
With the largest chemical engineering research faculty in the country, the Department of Chemical Engineering at MIT offers programs of research and teaching which span the breadth of chemical engineering with unprecedented depth in fundamentals and applications. The Department offers three levels of graduate programs, leading to Master’s, Engineer’s, and Doctor’s degrees. In addition, graduate students may earn a Master’s degree through the David H. Koch School of Chemical Engineering Practice, a unique internship program that stresses defining and solving industrial problems by applying chemical engineering fundamentals. Students in this program spend half a semester at each of two Practice School Stations, including Dow Chemical in Freeport, Texas, and Merck Pharmaceutical Manufacturing Division in West Point, Pennsylvania, in addition to one or two semesters at MIT.

For more information, contact
Chemical Engineering Graduate Office, 66-366
Massachusetts Institute of Technology, Cambridge, MA 02139-4307
Phone • (617) 253-4579; FAX • (617) 253-9695; E-Mail • info@chemgrad.mit.edu
WWW address • http://web.mit.edu/afs/athena/org/c/cheme/www/Titlepage.html
Faculty

1. Ralph T. Yang  Chair, Separations, adsorption, catalysis
2. Stacy G. Bike  Colloids, transport, electrokinetic phenomena
3. Dale E. Briggs  Coal processes
4. Mark A. Burns  Biochemical and field-enhanced separations
5. Brice Carnahan  Numerical methods, process simulation
6. H. Scott Fogler  Flow in porous media, microelectronics processing
7. John L. Gland  Surface science
8. Erdogan Gulari  Interfacial phenomena, catalysis, surface science
9. Costas Kravaris  Nonlinear process control, system identification
10. Ronald Larson  Polymers, complex fluids, fluid mechanics
11. Jennifer J. Linderman  Engineering approaches to cell biology
12. Susan Montgomery  Computers and multimedia in ChE instruction
13. David J. Mooney  Cellular and tissue engineering
14. Phillip E. Savage  Reaction pathways in complex systems
15. Johannes Schwank  Heterogeneous catalysis, surface science
16. Michael Solomon  Polymer and colloid rheology
17. Levi T. Thompson, Jr.  Catalysis, processing materials in space
19. James O. Wilkes  Numerical methods, polymer processing
20. Robert M. Ziff  Aggregation processes, statistical mechanics

For More Information, Contact:
Graduate Program Office, Department of Chemical Engineering / The University of Michigan / Ann Arbor, MI 48109-2136 / 313 763-1148
Graduate Study in Chemical Engineering

The Department of Chemical Engineering offers Graduate Programs leading to M.S. and Ph.D. degrees in Chemical Engineering. The faculty conduct fundamental and applied research in a variety of Chemical Engineering disciplines. The Michigan Biotechnology Institute, the Composite Materials and Structures Center, and the Crop and Food Bioprocessing Center provide a forum for interdisciplinary work in current high technology areas.

ASSISTANTSHIPS

Half-time graduate assistantships for incoming Master's candidates are expected to pay $15,690 per year plus a tuition waiver of six credits for Fall and Spring Semesters, four credits for Summer Semester. University paid health insurance is also provided. Theses are written on the project covered by the research assistantship.

FELLOWSHIPS

Available appointments pay up to $19,500 per year.

FOR ADDITIONAL INFORMATION WRITE

Chairperson
Department of Chemical Engineering
2527 Engineering Building
Michigan State University
East Lansing, Michigan 48824-1226

e-mail: grad_rec@egr.msu.edu
www: http://www.egr.msu.edu/ChE/

MSU is an Affirmative Action/Equal Opportunity Institution

- D.K. ANDERSON • Ph.D., 1960, University of Washington
  Johansen Crosby Professor
- K.A. BERGLUND • Ph.D., 1981, Iowa State University
  Sensors, Applied Spectroscopy, Food and Biochemical Engineering, Crystalization from Solution
- D.M. BREIDIS • Ph.D., 1981, Iowa State University
  Surface Phenomena in Crystallization Processes, Biochemical and Food Engineering, Bioadhesion
- B.E. DALE, Chairperson • Ph.D., 1979, Purdue University
  Biochemical Engineering, Bioremediation, Biomass Conversion, Protein Stability
- L.T. DRZAL • Ph.D., 1974, Case Western Reserve University
  Surface and Interfacial Phenomena, Adhesion, Composite Materials, Surface Characterization, Surface Modification of Polymers, Composite Processing
- 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, Processing of Polymer Blends and Composites, Computational Methods
- C.M. LASTOSKIE • Ph.D., 1994, Cornell University
  Process Dynamics of Environmental Systems, Adsorption in Porous Materials, Statistical Thermodynamics and Molecular Simulation
- C.T. LIRA • Ph.D., 1986, University of Illinois at Urbana-Champaign
  Thermodynamics and Phase Equilibria of Complex Systems, Adsorption, Supercritical Fluid Studies
- D.J. MILLER • Ph.D., 1982, University of Florida
  Kinetics and Catalysis, Reaction Engineering, Catalytic Conversion of Biomass-Based Materials
- R.J. MORGAN • Ph.D., 1968, University of Manchester
  High Performance Fibers, Polymer Matrices, Fast Processing, Composite Materials, Reliability and Durability
- R. NARAYAN • Ph.D., 1976, University of Bombay
  Polymer Blends and Alloys, Biodegradable Plastics, Low-Cost Composites Using Recycled/Reclaimed and Natural Polymers, Biodegradation and Composting Studies
- R.Y. OFOLI • Ph.D., 1994, Carnegie Mellon University
  Colloid and Interfacial Science: Colloid Stability, Adsorption of Proteins, Receptor-Ligand Interactions at the Liquid-Liquid Interface
- C.A. PETTY • Ph.D., 1970, University of Florida
  Fluid Mechanics, Turbulent Transport Phenomena, Solid-Fluid and Liquid-Liquid Separations, Hydrocyclones
- A.B. SCRANTON • Ph.D., 1990, Purdue University
  Polymer Science and Engineering, Polymer Complexation and Network Formation, Applications of NMR and Luminescence Spectroscopy, Molecular Modeling, Crosslinking Photopolymerizations
- B.W. WILKINSON • Professor Emeritus • Ph.D., 1958, Ohio State University
  Biochemical Engineering, Microbial Transport Processes, Synthesis Gas Fermentations, Metabolic Engineering, Microbial Ecology
- R.M. WORDEN • Ph.D., 1986, University of Tennessee
  Biochemical Engineering, Microbial Transport Processes, Synthesis Gas Fermentations, Metabolic Engineering, Microbial Ecology
Chemical Engineering

Michigan Technological University

Add your name to the ranks of the prestigious engineering alumni from Michigan Tech

Combine a first-rate chemical engineering education with the environmentally exciting surroundings of the Keweenaw Peninsula.

Michigan Tech. Established in 1885. One of four nationally-recognized research institutions in the state of Michigan. 6,000 undergraduate students, 800 graduate students.

Michigan Tech. One of the largest chemical engineering programs in the country, with a vital and focused graduate program.

Contact

Department of Chemical Engineering
Michigan Technological University
1400 Townsend Drive
Houghton, MI 49931-1295
906/487-3132
FAX 906/487-3213

Chemical Engineering Faculty

Process and plant design
Bruce A. Barna, Professor • Ph.D., New Mexico State University, 1985
Demixing-polymerization, polymer materials
Gerard T. Caneba, Associate Professor • Ph.D., University of California, Berkeley, 1985
Process control, neural networks, fuzzy logic control
Tomas B. Co, Associate Professor • Ph.D., Massachusetts, Amherst, 1988
Chemical process safety
Daniel A. Crowl, Professor and Dow Chair in Chemical Process Safety • Ph.D., University of Illinois, Urbana 1975
Metallurgical/nuclear engineering
Thomas G. Ellis, Associate Professor • Ph.D., Iowa State University, 1957
Excited state chemistry and transport processes
Edward R. Fisher, Professor and Department Chair • Ph.D., Johns Hopkins University, 1965
Process control, energy systems
Nam K. Kim, Associate Professor • Ph.D., Montana State University, 1982
Polymers, composites
Julia A. King, Assistant Professor • Ph.D., University of Wyoming, 1989

Polymer rheology, flow instabilities, complex fluids
Faith A. Morrison, Associate Professor • Ph.D., University of Massachusetts, Amherst 1988
Catalysis, ceramic processing, reactor design
Michael E. Mullins, Professor • Ph.D., University of Rochester, 1983
Cell and tissue engineering
David J. Odde, Assistant Professor • Ph.D., Rutgers University, 1995
Chemical process safety
Anton J. Pintar, Associate Professor • Ph.D., Illinois Institute of Technology, 1968
Environmental thermodynamics
Tony N. Rogers, Assistant Professor • Ph.D., Michigan Technological University, 1994
Surface science, catalysis
Kirk H. Schulz, Assistant Professor • Ph.D., Virginia Tech, 1991
Environmental and biochemical engineering
David R. Shonnard, Assistant Professor • Ph.D., University of California, Davis, 1991
Polymer science, polymer and composite processing
John G. Williams, Professor • Ph.D., Melbourne University, 1971

Michigan Technological University is an equal opportunity educational institution/equal opportunity employer.
Department of Chemical Engineering

offering M.S. and Ph.D. Degrees

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

Contact
Dr. P. Neogi or Dr. O.C. Sitton
Graduate Coordinators
Chemical Engineering Department
University of Missouri - Rolla
Rolla, Missouri 65409-1230
Telephone (573) 341-4417

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

D. FORCINITI (Ph.D., North Carolina State)
• Bioseparations • Thermodynamics • Statistical Mechanics

J. W. JOHNSON (Ph.D., Missouri)
• Electrode Reactions • Adsorption

A. I. LIAPIS (Ph.D., ETH-Zurich)
• Transport Phenomena • Adsorption/Desorption Fundamentals and Processes • Bioseparations • Chromatographic Separations • Chemical Reaction Engineering • Lyophilization

D. K. LUDLOW (Ph.D., Arizona State)
• Characterization of the Surfaces of Adsorbents and Catalysts • Applications of Fractal Geometry to Surface Morphology

D. B. MANLEY (Ph.D., Kansas)
• Thermodynamics • Vapor-Liquid Equilibrium • Process Development

N. C. MOROSOFF (Ph.D., Brooklyn Polytech)
• Plasma Polymerization • Membranes

P. NEOGI (Ph.D., Carnegie-Mellon)
• Interfacial and Transport Phenomena

G. K. PATTERSON (Ph.D., Missouri-Rolla)
• Mixing • Polymer Rheology • Computational Fluid Dynamics and Turbulent Transport

X B REED, JR. (Ph.D., Minnesota)
• Fluid Mechanics • Drop and Particle Mechanics • Transport Phenomena • Turbulence Structure • Turbulence Modeling, including Reactions

S. L. ROSEN (Ph.D., Cornell)
• Polymerization Reactions • Applied Rheology • Polymeric Materials

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

D. SOURLAS (Ph.D., UCLA)
• Process Control • Optimization

R. M. YBARRA (Ph.D., Purdue)
• Rheology of Polymer Solutions • Chemical Reaction Kinetics
Jennifer Brand - *University of California, San Diego*
  - Supercritical Fluid Processing; Natural Product Processing; Environmental Remediation

L. Davis Clements - *University of Oklahoma*
  - Computer-Aided Process Design; Process Synthesis; Fuels and Chemicals from Biomass

James Eakman - *University of Minnesota*
  - Computer-Aided Process Engineering; Solids Properties & Processing; Reaction Engineering

James Hendrix - *University of Nebraska*
  - Remediation of Mine Tailings Waste; Novel Analytical Chemistry; Non-Ideal Reactors

Gustavo Larsen - *Yale University*
  - Heterogeneous Catalysis; Spectroscopic Characterization of Catalysts

Lee Lauderback - *Purdue University*
  - Surface Analysis; Heterogeneous Catalysis

Hossein Noureddini - *University of Nebraska*
  - Production of Chemicals from Agricultural Products; Mathematical Modeling of Polymerization Kinetics

Delmar Timm - *Iowa State University*
  - Polymer Composites; Step-Wise Polymerization Kinetics; Kinetic Analysis Using GPC

Hendrik Viljoen - *University of Pretoria*
  - Plasma-Enhanced CVD; Detonation & Combustion; Ceramics

*For further information, write..............*

*Director of Graduate Studies*
*Department of Chemical Engineering*
*University of Nebraska*
*Lincoln, NE 68588-0126*

Also, please visit us at our web site at: [http://www.unl.edu/chemengr/](http://www.unl.edu/chemengr/)

Graduate admissions on-line applications and printable forms available at: [http://www.unl.edu/gradstud/gradadmission.html](http://www.unl.edu/gradstud/gradadmission.html)
The Department of Chemical Engineering, Chemistry and Environmental Science offers excellent opportunities for interdisciplinary research and graduate studies, particularly in the areas of hazardous waste treatment, materials science, and biotechnology. Both master's and doctoral degrees are offered in a growing program that has national and international research ties.

**Resources:**
- 20,000 sq. ft. of modern laboratory and computing facilities
- Internationally respected faculty
- Major research facilities in hazardous substance management and materials processing

**Support:**
- Over $2.5 million in annual research support from state, federal and industrial sponsors
- Financial assistance programs

**Flexibility:**
- Part-time or full-time
- Evening study
- Interdisciplinary research
- Diverse areas of specialization
- M.S. and Ph.D. degrees

For program information contact
Dr. Dana Knox, Graduate Advisor
Department of Chemical Engineering, Chemistry and Environmental Science
(201) 596-3599

For graduate admission information write or call (201) 596-3460

NJIT does not discriminate on the basis of sex, sexual orientation, race, handicap, veteran's status, national or ethnic origin or age in the administration of student programs. Handicap accessible facilities.
The University of New Mexico along with the Air Force’s Phillips Laboratory, Sandia and Los Alamos National Laboratories and local industry, make Albuquerque a major scientific and research center. The Chemical and Nuclear Engineering Department faculty are closely associated with the Center for Micro-Engineered Materials, the Center for Radioactive Waste Management, the Center for High Technology Materials, the Advanced Materials Laboratory and the Institute for Space and Nuclear Power Studies.

Faculty
Harold Anderson
C. Jeffrey Brinker
Joseph L. Cecchi, Chair
Abhaya K. Datye
David Kauffman
Toivo T. Kodas
Ronald E. Loehman
Gabriel P. López
Richard W. Mead
H. Eric Nuttall
Douglas M. Smith
Timothy L. Ward
Ebtisam S. Wilkins

Research Areas
- Plasma Processing
- Ceramics, Sol-Gel Processing, Porous Materials, Inorganic Membranes
- Semiconductor Manufacturing Technology, Plasma Etch and Deposition
- Catalysis, Interfaces, Advanced Materials
- Plant Design, Environmental Engineering
- Chemical Vapor Deposition & Etching
- Glass-metal and Ceramic-metal Bonding and Interfacial Reactions
- Organic Surfaces and Thin Films, Biomaterials
- Unit Operations, Resource Extraction
- Environmental Science, Colloid Science, Waste Transport Management
- Porous Material, Aerosol Physics
- Aerosol Materials Synthesis, Inorganic Membranes
- Biomedical Sensors, Waste Treatment

Albuquerque is a unique combination of the very old and the highly contemporary, the natural world and the manmade environment, the frontier town and the cosmopolitan city, a harmonious blend of diverse cultures and peoples. Albuquerque’s southwestern climate and rugged mountainous terrain provide plenty of opportunities for outdoor recreation such as skiing, hiking, camping and whitewater rafting.

The Chemical Engineering Program offers financial aid in the form of research assistantships paying $12-16,000 per year, plus tuition.

For more information, contact:
Toivo T. Kodas, Graduate Advisor
Chemical and Nuclear Engineering • The University of New Mexico
Albuquerque, NM 87131-1341
505.277.5431
505.277.5433 • FAX
++kodas@unm.edu

While you’re waiting for the Department packet, check out the ChNE Internet page at http://www-chne.unm.edu
DEPARTMENT OF CHEMICAL ENGINEERING

Biochemical Engineering • Catalysis, Kinetics, and Reaction Engineering
Computer-Aided Design and Manufacturing • Electronic Materials
Electrochemical Engineering • Environmental Engineering
Polymer Science and Engineering
Thermodynamics and Computer Simulation

FACULTY AND THEIR RESEARCH INTERESTS

Ruben G. Carbonell • Princeton
Bioseparations; Colloid and Surface Science; Multiphase Transport Phenomena

Joseph M. DeSimone • Virginia Tech
Polymerizations in Supercritical Fluids; Step-Growth Polymerizations; Heterophase Polymeric Solutions

Peter S. Fedkiw • Cal-Berkeley
Electrochemical Engineering; Electrocatalysis

Richard M. Felder • Princeton
Computer-Aided Manufacturing of Specialty Chemicals; Process Simulation and Optimization

James K. Ferrell • NC State
Waste Minimization; Heat Transfer; Process Control

Benny D. Freeman • Cal-Berkeley
Polymer Physical Chemistry

Christine S. Grant • Georgia Tech
Colloid and Surface Science; Environmental Engineering

Keith E. Gubbins • London
Molecular Simulation of Interfacial Phenomena; Nanoporous Materials

Carol K. Hall • Stony Brook
Statistical Thermodynamics; Computer Simulation; Polymers; Protein Folding

Harold B. Hopfenberg • MIT
Transport and Aging in Glassy Polymers; Controlled Release; Membranes; Barrier Packaging

Robert M. Kelly • NC State
Bioenergetics and Physiology of Microorganisms from Extreme Environments; Biocatalysts

Saad Khan • MIT
Polymer Rheology; Rheology of Reactive Polymer Solutions and Melts; Polymer Spectroscopy

Peter K. Kilpatrick • Minnesota
Interfacial and Surface Science; Biotechnology

H. Henry Lamb • Delaware
Heterogeneous Catalysis; Microelectronics; Surface Science

P. K. Lim • Illinois
Interfacial Phenomena; Homogeneous Catalysis; Free Radical Chemistry

David F. Ollis • Stanford
Photochemical and Biochemical Engineering

Michael R. Overcash • Minnesota
Environmental Engineering; Improved Manufacturing Productivity by Waste Reduction

Gregory N. Parsons • N.C. State
Semiconductor and Insulator Growth Chemistry; Physics of Amorphous Materials and Devices

Steven W. Peretti • Caltech
Genetic and Metabolic Engineering; Microbial, Plant and Animal Cell Culture; Bioremediation

George W. Roberts • MIT
Heterogeneous Catalysis; Reaction Kinetics and Engineering; Pollution Prevention

C. John Setzer • Ohio State
Plant and Process Economics and Management

Vivian T. Stannett, Emeritus • Brooklyn Poly
Pure and Applied Polymer Science

Inquiries to:
Professor Gregory N. Parsons, Recruiting Coordinator • (919) 515-7553 • parsons@che.ncsu.edu

Box 7905 • North Carolina State University • Raleigh, North Carolina 27695-7905
Annelise E. Barron, Ph.D., Berkeley, 1995
   Bioseparations, biopolymer engineering

Linda J. Broadbelt, Ph.D., Delaware, 1994
   Reaction engineering, kinetics modeling, polymer resource recovery

Wesley R. Burghardt, Ph.D., Stanford, 1990
   Polymer science, rheology

William C. Cohen, Ph.D., Princeton, 1960
   Process dynamics and automatic control

Buckley Crist, Jr., Ph.D., Duke, 1966
   Polymer science, thermodynamics, mechanics

Joshua S. Dranoff, Ph.D., Princeton, 1960
   Chemical reaction engineering, chromatographic separations

Thomas K. Goldstick, Ph.D., Berkeley, 1966
   Biomedical engineering, oxygen transport in the human body

Harold H. Kung, Ph.D., Northwestern, 1974
   Kinetics, heterogeneous catalysis

Michael L. Mavrovouniotis, Ph.D., MIT, 1989
   Computer-aided process engineering

William M. Miller, Ph.D., Berkeley, 1987
   Cell culture for biotechnology and medicine

Lyle F. Mockros, Ph.D., Berkeley, 1962
   Biomedical engineering, fluid mechanics in biological systems

Monica Olvera de la Cruz, Ph.D., Cambridge, 1984
   Statistical mechanics in polymer systems

Julio M. Ottino, Ph.D., Minnesota, 1979
   Fluid mechanics, chaos, mixing in materials processing

E. Terry Papoutsakis, Ph.D., Purdue, 1980
   Biotechnology of animal and microbial cells

Bruce E. Rittmann, Ph.D., Stanford, 1979
   In situ bioremediation, biofilms

Gregory Ryskin, Ph.D., Caltech, 1983
   Fluid mechanics, computational methods, polymeric liquids

Randall Q. Snurr, Ph.D., Berkeley, 1994
   Adsorption and diffusion in porous media, molecular modeling

John M. Torkelson, Ph.D., Minnesota, 1983
   Polymer science, membranes

Fall 1997
Chemical Engineering at Notre Dame

FACULTY

► J. F. Brennecke
► J. J. Carberry
► H. -C. Chang
► D. A. Hill
► J. C. Kantor
► D. T. Leighton, Jr.
► E. J. Maginn
► M. J. McCready
► P.J. McGinn
► A.E. Miller
► R. A. Schmitz
► M. A. Stadtherr
► W. C. Strieder
► A. Varma
► E. E. Wolf

RESEARCH AREAS

Advanced Ceramic Materials
Catalysis and Surface Science
Chemical Reaction Engineering
    Process Design
    Gas-Liquid Flows
Nonlinear Dynamics
Parallel Computing
Phase Equilibria
Polymer Science
Process Dynamics and Control
    Statistical Mechanics
Superconducting Materials
Supercritical Fluids
Suspension Rheology
Thermodynamics and Separations
Transport Phenomena
Environmentally Conscious Design

The University of Notre Dame offers a program of graduate study leading to a Master of Science or Doctor of Philosophy degree in Chemical Engineering. The requirements for a master's degree are normally completed in sixteen to twenty-four months. The doctoral program requires about four years of full-time study beyond the bachelor's degree. We accept applications from students whose undergraduate degrees are in areas of science or engineering other than chemical engineering.

Financially attractive fellowships and assistantships, which include a full-tuition waiver, are available to students pursuing either degree.

For further information, write or call
Dr. Joan F. Brennecke • Department of Chemical Engineering
University of Notre Dame • Notre Dame, Indiana 46556
Phone: 1-800-528-9487 E-mail: chegdept.1@nd.edu
www site: http://www.nd.edu/~chegdept/
Excellent facilities and a unique combination of research projects at the frontiers of science and technology.

Outstanding faculty and student body who are both dedicated and professional.

Attractive campus only minutes away from newly revitalized downtown Columbus.

Financial support ranging from $12,000 to $17,000 annually, plus tuition.

Close Relationships Between Graduate Students and Faculty

Excellent Opportunities for Personal and Professional Growth

For complete information, write or call

Professor Jacques L. Zakin • Department of Chemical Engineering
The Ohio State University • 140 W. 19th Avenue
Columbus, Ohio 43210-1180
Phone: (614) 292-6591

www address: http://www.erc.eng.osu.edu/che/ • e-mail address: che@osu.edu

Bhavik Bakshi, Massachusetts Institute of Technology 1992, Process Control, Intelligent Controllers, Wavelet Neural Networks, Systems Integration, Artificial Intelligence in Design, Planning, and Analysis

Robert S. Brodkey, Wisconsin 1952, Turbulent Motion, Mixing and Kinetics, Image Processing and Analysis, Reactor Design, and Rheology

Jeffrey J. Chalmers, Cornell 1988, Biochemical Engineering, Hydrodynamic Effects on Cells, Cell Separations, Biodegradation/Bioremediation

Kenneth R. Cox, Illinois-Urbana 1979, Molecular thermodynamics, Colloid and Interface Science, Physical Chemistry of Aqueous Systems, Polymer Phase Behavior, and Computational Chemistry

James F. Davis, Northwestern 1981, Artificial Intelligence in Diagnosis and Control, Intelligent Control, Data Interpretation, Pattern Recognition, Neural Networks, Systems Integration, Model Integration

L. S. Fan, West Virginia 1975, Fluidization, Powder Technology, Multiphase and Particulates Reaction Engineering, and Mathematical Modeling

Martin Feinberg, Princeton 1988, Reactors with Complex Chemistry, Reactor Optimization, Applied Mathematics

Morton H. Friedman, Michigan 1961, Biomedical Engineering and Hemodynamics

Kurt W. Koelling, Princeton 1992, Polymer Processing, Liquid Crystalline Polymers, Biodegradable Polymers, Polymer Rheology and Morphology

L. James Lee, Minnesota 1979, Polymer Processing, Composite Manufacturing, and Thermostet Polymers

Umit S. Ozkan, Iowa State 1984, Application of Heterogeneous Catalysis to Energy and Environmental Issues, Catalytic Materials, and Heterogeneous Kinetics

James F. Rathman, Oklahoma 1987, Chemical Reactions in Surfactant Solutions, Thermodynamics of Micelle Formation, Wetting and Adhesion, Interfacial Adsorption, and Transport

David L. Tomasko, Illinois-Urbana 1992, Intermolecular Interactions in Supercritical Fluids, Supercritical Fluid Extraction, Molecular Thermodynamics

Shang-Tian Yang, Purdue 1984, Biochemical Engineering and Biotechnology, Fermentation Processes, and Bioseparation

Jacques L. Zakin, New York 1959, Surfactant and Polymer Drag Reduction, Micellar Structures, Rheology, and Emulsions

The Ohio State University is an equal opportunity/affirmative action institution.
Ohio University

Chemical Engineering

Graduate Programs

The Department of Chemical Engineering offers programs leading to both the M.S. and Ph.D. degrees. The department is located in the Stocker Engineering Center, which recently (1994) underwent expansion and now contains some of the finest state-of-the-art equipment available. The department's activities are enhanced by the Stocker endowment, which was made possible by the generosity of Dr. C. Paul and Beth K. Stocker and which has now grown to over $14 million. The interest on this endowment is used to help support research efforts in such ways as providing competitive graduate fellowships and associateships, matching equipment funds, and seed money for new project areas.

Research Areas

Multiphase Flow and Associated Corrosion
Coal Conversion Technology and Desulfurization
Aerosol Science and Technology
Process Control
Separations
Energy and Environmental Engineering
Thin Film Materials
Chemical Reaction Engineering
Wastewater Treatment
Bioreactor Analysis
Downstream Processing of Proteins

Financial Aid

Financial support includes teaching and grant-related associateships and fellowships ranging from $10,000 to $15,000 per twelve months. In addition, students are granted a full tuition scholarship for both the regular and summer academic terms. Stocker Fellowships are available to especially well-qualified students.

The Faculty

Calvin H. Baloun, P.E., Emeritus (Ph.D., Cincinnati, 1962)
W. J. Russell Chen (Ph.D., Syracuse, 1974)
Nicholas Dinos (Ph.D., Lehigh, 1967)
Madan Gopal (Ph.D., Ohio, 1994)
Tingyue Gu (Ph.D., Purdue, 1991)
Daniel A. Gulino (Ph.D., Illinois, 1983)
W. Paul Jepson (Ph.D., Heriot-Watt, 1980)
Michael E. Prudich, Chair (Ph.D., West Virginia, 1979)
Darin Ridgway, P.E. (Ph.D., Florida State, 1990)
Kendree J. Sampson (Ph.D., Purdue, 1981)
Ben J. Stuart (Ph.D., Rutgers, 1995)
Valerie L. Young (Ph.D., Virginia Tech., 1992)

For More Information Contact:

Director of Graduate Studies
Department of Chemical Engineering, 172 Stocker Center • Ohio University, Athens OH 45701-2979
Visit our website at: http://www.ent.ohiou.edu/che

Ohio University is an affirmative action institution.
The University of Oklahoma
Graduate Studies in Chemical Engineering and Materials Science

Join us in research on critical technological problems in the following areas:
- Environmental
- Energy
- Polymers
- Bioengineering

Faculty and Research Interests

- Miguel J. Bagajewicz, Associate Professor
  - Process plant simulation and data reconciliation
  - Design of heat/mass-exchange networks for waste minimization applications
  - Mathematical background, algorithm development and process design applications of optimization theory
  - High temperature fuel-gas cleaning reactors
  - Modeling of fluid-solid diffusion-reaction problems

- Billy L. Crynes, Professor
  - Modeling of hydrocarbon pyrolysis
  - Surface effects during pyrolysis of hydrocarbons

- Brian P. Grady, Assistant Professor
  - Multiphase and block copolymers
  - Ion-containing polymers
  - X-ray, neutron and light scattering
  - Biodegradable and bioabsorbable polymers
  - Orientation and orientation mechanisms in polymers

- Roger G. Harrison, Jr., Associate Professor
  - Production of proteins and peptides using recombinant DNA technology
  - Separation and purification of biochemicals
  - Enzyme reactors
  - Protein engineering
  - Drug delivery systems
  - Applications of biotechnology to waste treatment

- Jeffrey H. Harwell, Conoco/DuPont Professor and Director
  - Tertiary oil recovery
  - Unconventional low energy separation processes
  - Mass transfer
  - Dynamics of multicomponent mass transfer processes
  - Surface phenomena
  - Adsorption kinetics

- Lloyd L. Lee, C. M. Slepcevich Professor
  - Thermodynamics
  - Molecular transport theory
  - Statistical mechanics
  - Structured liquids
  - Monte Carlo and molecular dynamics studies
  - Conformational solution theory
  - Natural gas properties
  - Polar fluids, ionic solutions, and molten salts
  - Surface adsorption
  - Turbulent flow

- Lance L. Lobban, Associate Professor
  - Catalytic reaction rate mechanisms and modeling
  - Partial oxidation of hydrocarbons
  - Fuel cells

- Richard G. Mallinson, Associate Professor
  - Chemical reaction engineering
  - Polymerization
  - Synthetic and alternative fuels

- Mathias U. Nollert, Assistant Professor
  - Biomedical engineering
  - Cellular metabolism and transport
  - Fluid transport
  - Fluid mechanics

- Edgar A. O'Rear, III, Professor
  - Catalysis
  - Surface chemistry and physics
  - Kinetics
  - Blood trauma associated with medical devices
  - Bioreheology
  - Organic chemistry
  - Coal technology

- Daniel E. Resasco, Associate Professor
  - Heterogeneous catalysis, reaction engineering and kinetics
  - Design of catalysts for pollutant abatement
  - Transport and adsorption in porous materials
  - Physical chemistry of surfaces
  - Characterization of ceramic supports

- Melissa M. Rieger, Assistant Professor
  - Electrochemical phenomena and electrochemical engineering
  - Alternative energy sources
  - Material systems and electrochemical processes in microelectronic processing
  - Opielectronic integration into silicon electronics
  - Electrochemical behavior of polymeric materials
  - Photochemical etching of silicon carbide
  - Porous silicon luminescence

- John F. Scamehorn, Asahi Glass Chair Professor
  - Surface and colloid science
  - Tertiary oil recovery
  - Detergency
  - Membrane separations
  - Adsorption
  - Pollution control
  - Polymers and paper and plastics deinking

- Robert L. Shambaugh, Professor
  - Polymerization chemistry
  - Polymer processing technology
  - Fiber spinning, texturing and extrusion
  - Wastewater engineering
  - Physicochemical treatment
  - Ozonation
  - Gas-liquid reactions

Call, Fax, Write or E-Mail:
Chairman, Graduate Program Committee
School of Chemical Engineering and Materials Science
The University of Oklahoma
100 E. Boyd, Room T-335
Norman, OK 73019-0628
Phone: (405) 325-5811
Fax: (405) 325-5813
E-Mail: chegrad@ou.edu

For more detailed information, visit our World Wide Web site at:
http://www.ou.edu/cems/OKChe/research.html
OSU's School of Chemical Engineering offers programs leading to M.S. and Ph.D. degrees. Qualified students receive financial assistance at nationally competitive levels.

Research Areas

- Adsorption
- Air Pollution
- Artificial Intelligence
- Biochemical Processes
- Corrosion
- Design
- Environmental Engineering
- Fluid Flow
- Gas Processing
- Hazardous Wastes
- Ion Exchange
- Kinetics
- Mass Transfer
- Modeling
- Phase Equilibria
- Polymers
- Process Control
- Process Simulation
- Thermodynamics

For more information contact
Dr. Robert L. Robinson
School of Chemical Engineering
Oklahoma State University
Stillwater, OK 74078
tree@OKWAY.OKSTATE.EDU
Chemical Engineering
M.S. and Ph.D.
Programs

Our programs reflect not only traditional chemical engineering fields but also technologies important to the Northwest's industries, such as electronic material processing, forest products, food science, and ocean products.

Oregon State is located only a short drive from the Pacific Ocean, white-water rivers, and hiking / skiing / climbing in the Cascade Mountains.

FACULTY

- G. N. Jovanovic
  Fine Particle Processing, Transport Phenomena

- S. Kimura
  Reaction Engineering, High-Temperature Materials

- J. G. Knudsen
  Heat Transfer

- M. D. Koretsky
  Electronic Materials Processing

- O. Levenspiel
  Fluidization, Chemical Reaction Engineering

- K. L. Levien
  Process Optimization and Control

- J. McGuire
  Protein Adsorption, Biofilm Development

- W. E. Rochefort
  Rheology, Characterization of Polymers

- G. L. Rorrer
  Biochemical Reaction Engineering

- C. E. Wicks
  Mass Transfer

Competitive research and teaching assistantships are available.

For further information, write:
Chemical Engineering Department
Oregon State University
103 Gleeson Hall
Corvallis, Oregon 97331-2702
University of Pennsylvania
Chemical Engineering

Pennsylvania's chemical engineering program is designed to be flexible while emphasizing the fundamental nature of chemical and physical processes. Students may focus their studies in any of the research areas of the department. The full resources of this Ivy League university, including the Wharton School of Business and one of this country's foremost medical centers, are available to students in the program. The cultural advantages, historical assets, and recreational facilities of a great city are within walking distance of the University.

For additional information, write:

Director of Graduate Admissions
Department of Chemical Engineering
311A Towne Building
University of Pennsylvania
Philadelphia, Pennsylvania 19104-6393

Stuart W. Churchill ■ Combustion, incineration, Czochralski crystallization, rate processes
Russell J. Composto ■ Polymeric materials science, surface and interface studies
Scott L. Diamond ■ Endothelial cell mechano-biology, drug and gene delivery, biotransport phenomena
Gregory C. Farrington ■ Electrochemistry, solid state and polymer chemistry
William C. Forsman ■ Polymer science and engineering, graphite intercalation
Eduardo D. Glandt ■ Classical and statistical thermodynamics, random media
Raymond J. Gorte ■ Heterogeneous catalysis, supported metals, zeolites
David J. Graves ■ Biochemical and biomedical engineering, biotechnology
Daniel A. Hammer ■ Cellular bioengineering, biointerfacial phenomena, adhesion
Mitchell Litt ■ Biorheology, biofluids, hemorheology, biomedical instrumentation
Alan L. Myers ■ Adsorption of gases and liquids, molecular simulation
Daniel D. Perlmutter ■ Chemical reactor design, gas-solid reactions, gel kinetics
John A. Quinn ■ Membrane transport, biochemical/biomedical engineering
Warren D. Seider ■ Process analysis, simulation, design, and control
Lyle H. Ungar ■ Artificial intelligence in process control, neural networks
T. Kyle Vanderlick ■ Thin-film and interfacial phenomena
John M. Vohs ■ Surface science, catalysis, electronic materials processing
Karen I. Winey ■ Polymer morphology, processing, and property interrelationships
Individuals with a B.S. degree in chemistry or other related areas are encouraged to apply.

For more information, contact:
Chairperson
Graduate Admissions Committee
Department of Chemical Engineering
The Pennsylvania State University
158 Fenske Laboratory
University Park PA 16802-4400
HTTP://GIBBS.CHE.PSU.EDU

Penn State is an affirmative action, equal opportunity university.
DEGREE PROGRAMS
PhD and MS in Chemical Engineering
MS in Petroleum Engineering

What is chemical engineering at Pitt?

A short answer:
- applied enzymology
- biochemical engineering
- biotechnology
- chemistry of fossil fuels
- coal science
- colloidal suspensions
- combustion
- flow through porous media
- heterogeneous catalysis
- kinetics
- microemulsions
- molecular thermodynamics
- organometallic chemistry
- petroleum engineering
- phase equilibria
- polymers
- process design
- protein engineering
- reaction engineering
- recycling technology
- separation science
- solids processing
- supercritical fluids
- surface chemistry
- transport phenomena

For a more detailed answer, and information about fellowships and applications, write or call the

Graduate Coordinator
Department of Chemical and Petroleum Engineering
1249 Benedum Hall
University of Pittsburgh
Pittsburgh, PA 15261
Phone: 412-624-9630

or visit us at our website
http://www.engrgng.pitt.edu/~chewww/

FACULTY
Mohammad M. Ataai
Anna C. Balazs
Eric J. Beckman
Harvey S. Borovetz*
Edward G. Cape*
Shiao-Hung Chiang
James T. Cobb, Jr.
Julie L. d'Itri

Robert M. Enick
Dan Farcasiu
William Federspiel*
James G. Goodwin, Jr.
Gerald D. Holder
J. Karl Johnson
George E. Klinzing
J. Thomas Lindt
Badie I. Morris
John F. Patzer*
Alan J. Russell
Jerome S. Schultz
Sindee Simon
John W. Tierney
William R. Wagner*
Irving Wender

* Joint appointment

University of Pittsburgh

The University of Pittsburgh is an affirmative action, equal opportunity institution
Come to New York City's Polytechnic University, where a dynamic research-oriented faculty carries on a tradition of excellence and innovation in chemical engineering.

For more information contact

Professor J. Mijovic • Department of Chemical Engineering, Chemistry, and Materials Science
Polytechnic University • Six MetroTech Center • Brooklyn, NY 11201 • Phone (718) 260-3525
Graduate Studies in Chemical Engineering

Purdue University

Faculty

L.F. Albright, Emeritus
R.P. Andres
O.A. Basaran
J.M. Caruthers
K.C. Chao, Emeritus
W.N. Delgass
F.J. Doyle
R.E. Eckert
E.I. Franses
R.A. Greenkorn
R.E. Hannemann
R.N. Houze
D.P. Kessler
H.S. Lackritz
J. Lauterbach
J.F. Pekny
N.A. Peppas
D. Ramkrishna
G.V. Reklaitis
E.M. Sevick-Muraca
J.L. Sinclair
R.G. Squires
G.T. Tsao
V. Venkatasubramanian
N.H.L. Wang
P.C. Wankat

Research Areas

Applied Mathematics
Artificial Intelligence
Biochemical Engineering
Biomedical Engineering
Catalysis and Reaction Engineering
Colloids and Interfacial Engineering
Process Operations and Design
Environmental Science
Fluid Mechanics
Fluid Particle Systems
Materials and Microelectronics Processing
Parallel Computing and Combinatorics
Polymer Science and Engineering
Separation Processes
Surface Science and Engineering
Thermodynamics and Statistical Mechanics
Transport Phenomena

Financial Assistance
Fellowships
Research Assistantships
Teaching Assistantships

Degrees Offered
Master of Science
Doctor of Philosophy

For More Information
Graduate Studies
Purdue University
1283 Chemical Engineering Bldg.
West Lafayette, Indiana 47907-1283
Phone: (765) 494-4057
Web Address: http://www.che.purdue.edu

Purdue is an equal access/equal opportunity university.
Graduate study from a different perspective.

Graduate study in the Department of Chemical Engineering at The University of Queensland, Australia, offers an opportunity to broaden your social and cultural perspectives while you are furthering your career development.

Situated in the vibrant Asia-Pacific region, the department has six research groups offering exciting areas for graduate study:
- Adsorption and Engineering Science
- Bioprocess Engineering
- Computer Aided Process Engineering
- Environmental Engineering
- Plastics and Material Rheology and Processing
- Particles and Fluids.

Join our 22 faculty and 140 Australian and international graduate students doing fundamental and applied research in areas such as:

- Adsorption
- Animal & Insect Cell Products
- Catalysis
- Chromatographic Separations
- Crystallisation
- Energy Resource Studies
- Environmental Control
- Environmental Systems
- Fermentation Processes
- Fluidisation and Particle Mechanics
- Granulation
- Hybridoma Technology
- Mineral Processing
- Numerical Analysis
- Particle Technology
- Polymer Processing
- Powder Processing
- Process Economics
- Process Simulation
- Rheology
- Solid Waste Management
- Transport Phenomena
- Water and Wastewater Treatment

Honours Graduates from any branch of Engineering, Science or Mathematics are invited to apply for our graduate program.

Scholarships are available.

To obtain more information or a copy of our postgraduate prospectus, please contact: Ms Mary-Anne Postgraduate Co-ordinator, The Department of Chemical Engineering, The University of Queensland, Brisbane Australia 4072 email: maryg@cheque.uq.oz.au Phone: 61 7 3365 4202 or fax: 61 7 3365 4199 or visit our World Wide Web page at http://www.cheque.uq.oz.au
Chemical Engineering at Rensselaer Polytechnic Institute

The Chemical Engineering Department at Rensselaer has long been recognized for its excellence in teaching and research. Its graduate programs lead to research-based M.S. and Ph.D. degrees and to a course-based M.E. degree. Programs are also offered in cooperation with the School of Management and Technology which lead to an M.E. in Chemical Engineering and to an MBA or the M.S. in Management. Owing to funding, consulting, and previous faculty experience, the department maintains close ties with industry. Department web site:

http://www.eng.rpi.edu/dept/chem-eng/

Located in Troy, New York, Rensselaer is a private school with an enrollment of some 6000 students. Situated on the Hudson River, just north of New York’s capital city of Albany, it is a three-hour drive from New York City, Boston, and Montreal. The Adirondack Mountains of New York, the Green Mountains of Vermont, and the Berkshires of Massachusetts are readily accessible. Saratoga, with its battlefield, racetrack, and Performing Arts Center (New York City Ballet, Philadelphia Orchestra, and jazz festival) is nearby.

Application materials and information from:

Graduate Services
Rensselaer Polytechnic Institute
Troy, NY 12180-3590
Telephone: 518-276-6789
e-mail: grad-admissions@rpi.edu
http://www.rpi.edu/dept/grad-services/

Faculty and Research Interests

Michael M. Abbott, abbotm2@rpi.edu
Associate Department Chair
Thermodynamics; equations of state; phase equilibria

Elmar R. Altwicker, altwie@rpi.edu
Spouted-bed combustion; incineration; mass transfer with chemical reaction

Georges Belfort, belfog@rpi.edu
Membrane separations; adsorption; biocatalysis; flow sensing with NMR

B. Wayne Bequette, bequeb@rpi.edu
Process modeling, control, design, and optimization

Henry R. Bungay III, bungah@rpi.edu
Wastewater treatment; biochemical engineering

Steven M. Cramer, crames@rpi.edu
Displacement, membrane, and preparative chromatography; environmental research

Arthur Fontijn, fontia@rpi.edu
Department Chair
Combustion; high-T kinetics; gas-phase reactions

William N. Gill, gillw@rpi.edu
Microelectronics; reverse osmosis; crystal growth; ceramic composites

Howard Littman, littmh@rpi.edu
Fluidization; spouting fluid/particle systems

Charles Muckenfuss, Professor Emeritus

E. Bruce Nauman, nauman@rpi.edu
Recycling of mixed plastics; structure and properties of polymers; polymer devolatilization

Joel L. Plawsky, plawsky@rpi.edu
Electronic and photonic materials; interfacial phenomena

Todd M. Przybycien, przybt@rpi.edu
Protein aggregation and adsorption phenomena; protein separations, formulation, and delivery

Hendrick C. Van Ness, Institute Professor Emeritus

Peter C. Wayner, Jr., wayner@rpi.edu
Heat transfer; interfacial phenomena
Graduate Study in Chemical Engineering at Rice University

The University
- Privately endowed coeducational school
- 2600 undergraduate students
- 1300 graduate students
- Quiet and beautiful 300-acre tree-shaded campus
- 3 miles from downtown Houston
- Architecturally uniform and aesthetic campus

The Department
- M.Ch.E., M.S., and Ph.D. degrees
- Approximately 75 graduate students (predominantly Ph.D.)
- Stipends and tuition waivers for full-time students
- Special fellowships with high stipends for outstanding candidates

The City
- Large metropolitan and cultural center
- Petrochemical capital of the world
- Industrial collaboration and job opportunities
- World renowned research and treatment medical center
- Professional sports
- Close to recreational areas

Research Interests
- Applied Mathematics
- Biochemical Engineering
- Biomedical Engineering
- Equilibrium Thermodynamic Properties
- Fluid Mechanics
- Interfacial Phenomena
- Kinetics and Catalysis
- Polymer Science
- Process Control
- Reaction Engineering
- Rheology
- Statistical Mechanics
- Tissue Engineering
- Transport in Porous Media
- Transport Processes
- Transport Properties

Send Applications and Inquiries to
Chair, Graduate Committee
Department of Chemical Engineering, MS-362
Rice University
6100 S. Main St.
Houston, TX 77005-1892

Additional information is available electronically through our World Wide Web home page located at http://riceinfo.rice.edu/~dek/CENG/index.html

Fall 1997

Faculty
- William W. Akers
  (Michigan, 1950)
- Constantine D. Armeniades
  (Case Western Reserve, 1969)
- Thomas A. Badgwell
  (Texas, 1992)
- Walter Chapman
  (Cornell, 1988)
- Sam H. Davis, Jr.
  (MIT, 1957)
- Derek C. Dyson
  (London, 1966)
- J. David Hellums
  (Michigan, 1961)
- Joe W. Hightower
  (Johns Hopkins, 1963)
- George J. Hirasaki
  (Rice, 1967)
- Riki Kobayashi
  (Michigan, 1951)
- Larry V. McIntire
  (Princeton, 1970)
- Antonios G. Mikos
  (Purdue, 1988)
- Clarence A. Miller
  (Minnesota, 1969)
- Mark A. Robert
  (Swiss Fed. Inst. of Tech., 1980)
- Ka-Yiu San
  (CalTech, 1984)
- Jacqueline Shanks
  (CalTech, 1989)
- Kyriacos Zygourakis
  (Minnesota, 1981)
Department of Chemical Engineering

University of Rochester

Graduate Study and Research leading to M.S. and Ph.D. degrees
Fellowships to $18,000

S. H. CHEN, Ph.D. 1981, Minnesota
  Polymer Science and Engineering • Transport Phenomena • Optical Materials

E. H. CHIMOWITZ, Ph.D. 1982, Connecticut
  Critical Phenomena • Statistical Mechanics of Fluids • Computer-Aided Design

R. H. HEIST, Ph.D. 1972, Purdue
  Nucleation • Aerosols • Ultrafine Particles

S. A. JENSEN, Ph.D. 1985, Minnesota
  Polymer Science and Engineering • Materials Chemistry • Optoelectronic and Photonic Materials and Devices

J. JORNE, Ph.D. 1972, California (Berkeley)
  Electrochemical Engineering • Microelectronics Processing • Theoretical Biology

  Biomedical Engineering • Lung Surfactant • Molecular Biophysics

H. J. PALMER, Ph.D. 1971, Washington (Seattle)
  Interfacial Phenomena • Phase Transfer Reactions • Mass Transfer • Bioengineering

S. V. SOTIRCHOS, Ph.D. 1982, Houston
  Reaction Engineering • Transport and Reaction in Porous Media • Processing of Ceramic Materials and Composites

J. H. D. WU, Ph.D. 1987, M.I.T.
  Biochemical Engineering • Fermentation • Biocatalysis • Bone Marrow Tissue Engineering • Genetic and Protein Engineering

For further information and application, write

Graduate Admissions • Department of Chemical Engineering
University of Rochester • Rochester, New York 14627
Phone: (716) 275-4042 • Fax: (716) 442-6686
e-mail: gradadm@che.rochester.edu

Chemical Engineering Education
Research Areas

Biotechnology • Chemical Engineering Science • Environmental Engineering • Pharmaceutical Engineering • Polymers

Faculty

- Helen M. Buettner, Associate Professor and Graduate Director; Ph.D., University of Pennsylvania, 1987 • Applied neurobiology, cell motility, cell-substrate interactions, crystallization
- Yee C. Chiew, Professor; University of Pennsylvania, 1984 • Statistical thermodynamics, microscopic structures of fluids and particle systems, interfacial phenomena
- Alkis Constantinides, Professor and Chair; D.E.Sc., Columbia University, 1970 • Biochemical engineering, optimization and control of fermentation processes, applied numerical analysis, artificial intelligence
- Peter Couchman, Professor; Ph.D., University of Virginia, 1976 • Thermodynamics, transition, and equation of state behavior of single and multicomponent systems, particularly polymers, surface phenomena
- Burton Z. Davidson, Professor; Ph.D., P.E., Northwestern University, 1963 • Systems simulation and optimization, environmental engineering, health and safety engineering management
- Panos G. Georgopoulos, Associate Professor; Ph.D., California Institute of Technology, 1986 • Atmospheric/environmental chemical engineering, turbulent transport, biohydrodynamics, modeling
- Benjamin J. Glasser, Assistant Professor; Ph.D., Princeton, 1995 • Multiphase flows and reactor granular materials and particulate suspensions; nonlinear dynamics of transport processes
- Masanori Hara, Professor; Ph.D., Kyoto University, 1981 • Polymer physics; polymer chemistry, polymer blends and composites, ionic polymers
- David S. Kossen, Professor; Ph.D., Rutgers University, 1986 • Hazardous waste management, in-situ and on-site remediation, leaching, contaminant fate and transport in wastes, soils, and groundwater
- Prabhakar V. Moghe, Assistant Professor; Ph.D., University of Minnesota, 1993 • Tissue engineering: skin, liver cell-biocomposites interactions, biodegradable polymers in medicine, cardiovascular materials
- Fernando Muzzio, Associate Professor; Ph.D., University of Massachusetts, 1991 • Transport phenomena, mixing, chaotic flows, powder technology
- Balaji Narasimhan, Assistant Professor; Ph.D., Purdue University, 1996 • Transport phenomena in polymers, dynamics of entangled polymers, magnetic resonance imaging, controlled drug delivery
- Brian A. Newman, Professor; Ph.D., Bristol, 1966 • Structure and morphology of electroactive polymers: X-ray diffraction studies of polymers; high-pressure polymer physics
- Henrik Pedersen, Professor; Ph.D., Yale University, 1978 • Biochemical engineering, immobilized enzymes, plant cell biotechnology, fiber-optic sensors
- Carlos B. Rosas, Visiting Professor and Administrative Director, Pharmaceutical Engineering Program; M.E., Stevens Institute of Technology, 1968 • Fine chemicals, pharmaceuticals, and biologicals
- Jerry I. Scheinbeim, Professor; Ph.D., University of Pittsburgh, 1975 • Structure-electrical properties of polymers; dielectric, piezoelectric, pyroelectric, and ferroelectric properties of electroactive polymers
- Shaw S. Wang, Professor; Ph.D., Rutgers University, 1970 • Kinetics and thermodynamics of food process engineering, and studies of biochemical and biological processes.
- Martin L. Yarmush, Visiting Professor; Ph.D., Rockefeller University, 1979; M.D., Yale University, 1984 • Applied immunology, artificial organs, bioseparations, protein engineering, biotechnology

FELLOWSHIPS, TRAINEESHIPS, AND ASSISTANTSHIPS AVAILABLE

For further information contact:
Graduate Program • Department of Chemical and Biochemical Engineering • Rutgers, The State University of New Jersey • Piscataway, NJ 08855-0909 • Phone (908) 445-4950 • Fax (908) 445-2421
E-mail: chemail@sol.rutgers.edu • http://sol.rutgers.edu/

Fall 1997
The University of South Carolina

Graduate Studies in
CHEMICAL ENGINEERING

The Department of Chemical Engineering at the University of South Carolina is booming! External research funding is at an all-time high—exceeding $4,000,000 per year—and the department is still growing with a charter to increase its faculty size by at least one more faculty member. As a result, this progressive department, with its young (average age < 40) and dynamic faculty, is already recognized as one of the top programs in the Southeast. Chemical engineering occupies over one-third of the new 220,000-square-foot John E. Swearingen Engineering Center, where the faculty teach and conduct research in state-of-the-art facilities. In addition, programs are offered that lead to both MS and PhD degrees; and PhD candidates are offered full tuition waiver and highly competitive, twelve-month stipends ranging from $1,575 to $1,975 per month. So, come to one of the fastest growing areas in the country, enjoy the beautiful weather and the ideal location (1.5 hrs to the beach, 2 hrs to the mountains), and be part of the explosion in Chemical Engineering at the University of South Carolina.

► Stipend Levels
$17,700 to $23,700/yr
Full Tuition Waiver
Twelve-Month Stipends

► Faculty
M.D. Amiridis, Wisconsin
P.B. Balbuena, Texas
C.L. Bolton, Princeton
F.A. Gadala-Maria, Stanford
J.H. Gibbons, Pittsburgh
K.A. Kosanovich, Notre Dame
M.A. Matthews, Texas A&M
T. Papathanasiou, McGill
H.J. Ploehn, Princeton
B.N. Popov, Illinois
J.A. Ritter, SUNY Buffalo
T.G. Stanford, Michigan
V. Van Brunt, Tennessee
J.W. Van Zee, Texas A&M
J.W. Weidner, NC State
R.E. White, Berkeley

► Research Areas
Adsorption Technology
Batteries and Fuel Cells
Colloids and Interfaces
Composite Materials
Corrosion Engineering
Crossflow Filtration
Electrochemistry
Environmental Restoration
Heterogeneous Catalysis
Numerical Methods
Phase Equilibria
Pollution Prevention
Process Control
Process Design
Rheology
Separations
Sol-Gel Processing
Solvent Extraction
Surface Science
Surface Spectroscopy
Supercritical Fluids
Waste Management
Waste Processing

► For further information, contact
The Graduate Director
Department of Chemical Engineering
Swearingen Engineering Center
University of South Carolina
Columbia, South Carolina 29208
phone: (800) 763-0527
fax: (803) 777-8265
www.engr.sc.edu/chem/
Multidisciplinary environment, consisting of chemical and polymer engineering, chemistry, and biology

Site of two major polymer engineering research centers; Polymer Processing Institute, Highly Filled Materials Institute

Scenic campus overlooking the Hudson River and metropolitan New York City

Close to the world’s center of science and culture

At the hub of major highways, air, rail, and bus lines

At the center of the country’s largest concentration of research laboratories and chemical, petroleum, pharmaceutical, and biotechnology companies

GRADUATE PROGRAMS IN CHEMICAL ENGINEERING

Full and part-time
Day and evening programs

• MASTER’S
• CHEMICAL ENGINEER
• PH.D.

For application, contact:
Office of Graduate Studies
Stevens Institute of Technology
Hoboken, NJ 07030
201-216-5234

For additional information, contact:
Department of Chemical Engineering
Stevens Institute of Technology
Hoboken, NJ 07030
201-216-5546

Financial Aid is Available to qualified students.

Stevens Institute of Technology does not discriminate against any person because of race, creed, color, national origin, sex, age, marital status, handicap, liability for service in the armed forces or status as a disabled or Vietnam era veteran.

Fall 1997
Piece together the elements of a great graduate experience...

The Research

Graduate students and faculty working together to reach common goals – that partnership is at the heart of the University of Tennessee-Knoxville's Department of Chemical Engineering. It's a partnership that works, creating exciting and productive research in six major areas: (1) bio-process engineering, (2) molecular science and engineering, (3) separations and transport phenomena, (4) computer-aided process simulation and design, (5) polymer and composite processing, and (6) process control. These research programs reach out to other engineering and science departments, to the nearby Oak Ridge National Laboratory, and to industry, forming larger partnerships and creating an unsurpassed research environment.

The Faculty

- Paul R. Bienkowski (Ph.D., Purdue, 1975) - Bioprocessing, Thermodynamics
- Donald C. Bogue (Ph.D., Delaware, 1960) - Polymers, Rheology
- Duane D. Bruns (Ph.D., Houston, 1974) - Process Control, Modeling
- Robert M. Counce (Ph.D., Tennessee, 1980) - Separations and Transport, Environmental
- Peter T. Cummings (Ph.D., Melbourne, 1980) - Molecular Thermodynamics, Design, Environmental
- George C. Frazier (D.Eng., Johns Hopkins, 1962) - Bioprocessing, Kinetics
- Paul D. Frymier (Ph.D., Virginia, 1995) - Biotechnology, Bioremediation, Environmental
- David J. Keffer (Ph.D., Minnesota, 1996) - Molecular Modeling of Adsorption, Diffusion and Reaction in Zeolites
- Charles F. Moore (Ph.D., Louisiana State, 1969) - Process Control
- John W. Prados (Ph.D., Tennessee, 1957) - Safety and Risk Assessment
- Tsewei Wang (Ph.D., M.I.T., 1977) - Process Control, Bioprocessing
- Frederick E. Weber (Ph.D., Minnesota, 1982) - Computer-Aided Design, Radiation Chemistry

Adjunct and Part-Time Faculty at Oak Ridge National Laboratory

- Charles H. Byers (Ph.D., Berkeley): Separations and Transport
- Hank D. Cochran (Ph.D., M.I.T.): Thermodynamics, Statistical Mechanics
- Brian H. Davison (Ph.D., Caltech): Biotechnology
- Terrence L. Donaldson (Ph.D., Pennsylvania): Biotechnology, Kinetics, Mass Transfer
- Jack S. Watson (Ph.D., Tennessee): Separations and Transport, Nuclear Fusion

The Next Step

For additional information contact:
Department of Chemical Engineering
University of Tennessee-Knoxville
419 Dougherty Hall
Knoxville, TN 37996-2200
Phone: (423) 974-2421
E-mail: cheinfo@utk.edu
World Wide Web: http://flory.engr.utk.edu/che

The University

Founded in 1794 as Blount College, the first non-sectarian college west of the Appalachians, The University of Tennessee today is the state’s largest university and Land-Grant institution with about 17,000 undergraduates, 7,500 graduate and professional students, and a faculty of 1,600. The University of Tennessee is located in Knoxville near the headwaters of the Tennessee River. Within an hour's drive are six Tennessee Valley Authority lakes and the Great Smoky Mountains National Park. The Knoxville metropolitan area has a population of 600,000 but enjoys a pleasant, generally uncrowded atmosphere and consistently ranks among the nation’s top ten metropolitan areas in surveys on quality of life. East Tennessee has a four-season climate, ranging from summer temperatures in the 90’s to winter temperatures cold enough for snow skiing in nearby mountain resorts.

TENNESSEE
The University of Texas at Austin's Department of Chemical Engineering is a cutting-edge, well-funded program. The Department has been among the top five in the U.S. in sponsored research and Ph.D. degrees granted for the last five years. Both the M.S. and the Ph.D. degrees are offered, with nearly all students pursuing the Ph.D. Fellowships and research assistantships are provided, including tuition and fees.

David Allen (Caltech) • environmental modeling, reaction engineering
Joel W. Barlow (University of Wisconsin) • polymer blends, properties, processing
Roger T. Bonnecaze (Caltech) • suspension rheology, transport phenomena, electrical impedance tomography
James R. Brock (University of Wisconsin) • aerosols, electronic materials processing
Thomas F. Edgar (Princeton University) • process modeling, control, optimization
John G. Ekerdt (University of California, Berkeley) • catalysis, electronic materials chemistry
Bruce Eldridge (University of Texas) • separations research
James R. Fair (University of Texas, Austin) Emeritus • process design, separation processes
George Georgiou (Cornell University) • microbial, protein biotechnology
Peter Green (Cornell University) • materials science • polymer melts
Adam Heller (Hebrew University) • electrochemical biosensing, environmental photoelectrochemistry
David M. Himmelblau (University of Washington) • artificial neural networks, fault detection and diagnosis
Keith P. Johnston (University of Illinois) • polymer and surface thermodynamics, supercritical fluid science
William J. Koros (University of Texas, Austin) • membrane and structure-permeability relationships for polymers
Douglas R. Lloyd (University of Waterloo) • polymeric membrane formation, liquid separations
C. Buddie Mullins (Caltech) • surface science, molecular beams, semiconductor thin-film growth
Donald R. Paul (University of Wisconsin) • polymer blends, membranes, barrier materials
Joseph Qin (University of Maryland) • process modeling and control
Gary T. Rochelle (University of California, Berkeley) • air pollution control, reactive mass transfer
Isaac C. Sanchez (University of Delaware) • statistical thermodynamics of polymer liquids and solutions
Robert S. Schechter (University of Minnesota) Emeritus • surface phenomena, flow in porous media with reaction
Christine Schmidt (University of Illinois) • biotechnology
Hugo Steinfink (Polytechnic University, New York) • crystal chemistry, structure-property relationship
James E. Stice (Illinois Institute of Technology) Emeritus • engineering teaching effectiveness, process control
Isaac Trachtenberg (Louisiana State University) • semiconductor materials processing
C. Grant Willson (University of California, Berkeley) • polymer synthesis, photochemical processing

Inquiries should be sent to
Graduate Advisor • Department of Chemical Engineering • University of Texas • Austin, TX 78712-1062
(512) 471-6991; Fax (512) 475-7824: utgrad@che.utexas.edu
Texas A&M University

- Large Graduate Program
- Approximately 120 Graduate Students
- Strong Ph.D. Program • 1/1 Ph.D./MS Student Ratio
- Diverse Research Areas
- Top 10 in Research Funding
- Quality Living / Work Environment
- Financial Aid to All Qualified Students
  • Up to $21,600/yr plus Medical Insurance Benefits

RESEARCH AREAS

- Biochemical Engineering/Bioprocessing
- Biomedical/Genetic/Metabolic Engineering
- Composite Materials and Asphalts
- Environmental Remediation/Pollution Prevention
- Gas Sweetening
- Interfacial Transport
- Kinetics, Catalysis and Reaction Engineering
- Microelectronic Materials
- Molecular Simulations
- Polymers
- Process Control/Computer-Aided Process Design and Modeling
- Separations/Adsorption/Ion Exchange
- Supercritical Phenomena/Technology
- Thermodynamics

For More Information

Graduate Admissions Office • Department of Chemical Engineering • Dwight Look College of Engineering
Texas A&M University • College Station, Texas 77843-3122
Phone (409) 845-3361 • Website http://www-chen.tamu.edu

R.G. Anthony, Head • Ph.D., University of Texas, 1966
Catalysis, reaction engineering ion exchange
A. Akgerman, Associate Head • Ph.D., University of Virginia, 1971
Chevron II Professor
Reaction engineering, waste treatment
L.A. Archer, Ph.D. • Stanford University, 1993
Polymers, rheology
John T. Baldwin, Ph.D. • Texas A&M University, 1968
Process Design
D.B. Bukur, Ph.D. • University of Minnesota, 1974
Reaction engineering, math methods
J.A. Bullin, Ph.D. • University of Houston, 1972
Gas sweetening, asphalt characterizations
R. Darby, Ph.D. • Rice University, 1972
Rheology, polymers
R.R. Davison, Ph.D. • Texas A&M University, 1962
Asphalt characterization
L.D. Durbin, Ph.D. • Rice University, 1961
Process control
P.T. Eubank, Ph.D. • Northwestern University, 1961
Joe M. Nesbitt Professor
D.M. Ford, Ph.D. • University of Pennsylvania, 1996
Molecular modeling/transport
C.J. Glover, Ph.D. • Rice University, 1974
Polymer solutions
T.A. Good, Ph.D. • University of Wisconsin-Madison, 1996
Biomedical Engineering
K.R. Hall, Ph.D. • University of Oklahoma, 1967
Director of TRC
D.T. Hanson, Ph.D. • University of Minnesota, 1968
Biochemical engineering
C.D. Holland, Ph.D. • Texas A&M University, 1953
Professor Emeritus
J.C. Holste, Ph.D. • Iowa State University, 1973
Separation processes, distillation, unsteady-state processes
J.C. Slattery, Ph.D. • University of Wisconsin, 1959
Jack E. and Sarah Brown Chair
Michael V. Pishko, Ph.D. • University of Texas at Austin, 1992
Bioengineering
J.C. Slattery, Ph.D. • University of Wisconsin, 1959
Jack E. and Sarah Brown Chair
Michael V. Pishko, Ph.D. • University of Texas at Austin, 1992
Bioengineering
J.C. Slattery, Ph.D. • University of Wisconsin, 1959
Jack E. and Sarah Brown Chair
A.T. Watson, Ph.D. • California Institute of Technology, 1979
Porous media, math modeling
The Chemical & Environmental Engineering Department at the University of Toledo offers a graduate program leading to both MS and PhD degrees. The Department recently moved to state of the art facilities in Nitschke Hall (pictured to the left) and is experiencing a period of rapid growth. Our dynamic, young faculty offer a variety of research opportunities in contemporary areas of engineering science.

**Martin A. Abraham**, Professor  
*PhD, University of Delaware*  
Environmental Reaction Engineering, Supercritical Fluids, Catalytic Processes

**Kenneth J. Dewitt**, Professor  
*PhD, Northwestern University*  
Transport Phenomena, Mathematical Modeling & Numerical Methods

**Saleh Jabarin**, Professor  
*PhD, University of Massachusetts*  
Physical Properties of Polymers, Polymer Orientation & Crystallization

**Steven E. LeBlanc**, Professor & Chair  
*PhD, University of Michigan*  
Environmental, Membrane Processes, Nonlinear Dynamics & Control

**G. Glenn Lipscomb**, Associate Professor  
*PhD, University of California at Berkeley*  
Membrane Separations, Polymer Science & Engineering

**Arunan Nadarajah**, Associate Professor  
*PhD, University of Florida*  
Transport Phenomena, Protein Crystallization

**Bruce E. Poling**, Professor  
*PhD, University of Illinois*  
Thermodynamics & Physical Properties

**Constance A. Schall**, Assistant Professor  
*PhD, Rutgers*  
Enzyme Kinetics, Crystallization, Soils Characterization & Remediation

**Sasidhar Varanasi**, Professor  
*PhD, State University of New York at Buffalo*  
Colloidal & Interfacial Phenomena, Enzyme Kinetics, Membrane Transport

Send Inquiries to:  
Graduate Program Director  
Chemical & Environmental Eng.  
University of Toledo  
2801 W. Bancroft  
Toledo, OH 43606-3390  
Phone: (419) 530-8080  
Fax: (419) 530-8086  
http://www.che.utoledo.edu
96 Years of Chemical Engineering at Tufts University

M.S. and Ph.D. Programs in Chemical and Biochemical Engineering

RESEARCH

Chemical Engineering Fundamentals
♦ Crystallization
♦ Heterogeneous Catalysis
♦ Membrane Science and Technology

Materials and Interfaces
♦ Biomolecular Materials
♦ Composite Materials
♦ Plasma Polymerization of Thin Films
♦ Polymer and Ceramic Science

Biochemical Engineering
♦ Biopolymer Engineering
♦ Bioseparations
♦ Fermentation
♦ Protein Refolding

Environmental Engineering
♦ Air Pollution Control
♦ Enviromental Catalysis
♦ Biodegradation

FACULTY

Jerry H. Meldon, Dept. Chair
Ph.D., M.I.T. (1973)

Gregory Botsaris
Ph.D., M.I.T. (1965)

Eliana De Bernardez Clark

Maria Flytzani-Stephanopoulos
Ph.D., Minnesota (1978)

David L. Kaplan
Ph.D., Syracuse (1978)

Daniel F. Ryder

Nakho Sung
Ph.D., M.I.T. (1972)

Martin V. Sussman
Ph.D., Columbia (1958)

Kenneth A. Van Wormer

For further information, please contact

Chair of Graduate Studies
Department of Chemical Engineering
Tufts University
4 Colby Street
Medford, MA 02155

Tel. 617.627.3900 • Fax 617.627.3991 • chemstudent@Infonet.Tufts.Edu
Faculty and Research Areas

Daniel C.R. DeKee • Rheology of Natural and Synthetic Polymers • Constitutive Equations • Transport Phenomena and Applied Mathematics

Richard D. Gonzalez • Synthesis and Characterization of Supported Metal Catalysts • Fundamental Studies in Reactor Design • In-situ Spectroscopic Methods • Reactions in Organized Media

Vijay T. John • Biomimetic and Nanostructured Materials • Interfacial Phenomena • Polymer-Ceramic Composites • Surfactant Science

Daniel J. Lacks • Molecular Simulation • Thermodynamics of Condensed Phases • Dynamical Processes in Solids • Physical Properties of Polymer Materials • Density Functional Theory

Victor J. Law • Modeling Environmental Systems • Nonlinear Optimization and Regression • Transport Phenomena • Numerical Methods

Brian S. Mitchell • Fiber Technology • Materials Processing • Composites

Kim C. O’Connor • Animal-Cell Technology • Organ/Tissue Regeneration • Recombinant Protein Expression

Kyriakos D. Papadopoulos • Colloid Stability • Coagulation • Transport of Multi-Phase Systems Through Porous Media • Colloidal Interactions

Peter N. Pintauro • Electrochemical Engineering • Membrane Separations • Electro-organic Synthesis • Environmental Remediation

For Additional Information, Please Contact

Graduate Advisor
Department of Chemical Engineering
Tulane University • New Orleans, LA 70118
Phone (504) 865-5772 • E-mail koc@mailhost.tcs.tulane.edu

Tulane is located in a quiet, residential area of New Orleans, approximately six miles from the world-famous French Quarter. The chemical engineering department currently enrolls approximately 40 full-time graduate students. Graduate fellowships include a tuition waiver plus stipend.
Engineering the World

The University of Tulsa

The University of Tulsa is Oklahoma's oldest and largest independent university. Approximately 4,900 students pursue more than 70 major fields of study and graduate programs in more than 25 disciplines.

Tulsa, Oklahoma

Off-campus activities abound in Tulsa, one of the nation's most livable cities. Our temperate climate, with four distinct seasons, is perfect for year-round outdoor activities. With a metropolitan population of 450,000, the city of Tulsa affords opportunities for students to gain internship and work experience in its dynamic data processing, petroleum, medical, and financial industries. One can also enjoy world-class ballet, symphony and theatre performances, and exhibits in the cultural community. Annual events include Mayfest, Oktoberfest, the Chili Cook-off and Bluegrass Festival, the Tulsa Run, and the Jazz and Blues festivals.

Chemical Engineering at TU

TU enjoys a solid international reputation for expertise in the petroleum industry, and offers environmental and biochemical programs. The department places particular emphasis on experimental research, and is proud of its strong contact with industry.

The department offers a traditional Ph.D. program and three master's programs:
- Master of Science degree (thesis program)
- Master of Engineering degree (a professional degree that can be completed in 18 months without a thesis)
- Special Master's degree for nonchemical engineering undergraduates

Financial aid is available, including fellowships and research assistantships.

The Faculty

T. Ariman • Particulate science and technology, multiphase separation processes
K.D. Luks • Thermodynamics, phase equilibria
F.S. Manning • Industrial pollution control, surface processing of petroleum
C.A. Schall • Crystallization, enzyme kinetics
K.L. Sublette • Fermentation, biocatalysis, biological waste treatment
K.D. Wisecarver • Multiphase reactors, multiphase flows

Further Information
Graduate Program Director • Chemical Engineering Department
The University of Tulsa • 600 South College Avenue • Tulsa, Oklahoma 74104-3189
Phone (918) 631-2975 • Fax (918) 631-3268
E-mail: che_kw@centum.utulsa.edu • Graduate School application: 1-800-882-4723

The University of Tulsa has an Equal Opportunity/Affirmative Action Program for students and employees.
Robert J. Bayuzick (Ph.D., Vanderbilt)
Microgravity processing of materials, nucleation and growth, rapid solidification.

Kenneth A. Debelak (Ph.D., Kentucky)
Artificial intelligence in process control; coal conversion with emphasis on particle structure and diffusional processes; hazardous waste minimization.

Tomlinson Fort (Ph.D., Tennessee)
Adsorption; surfactant spreading on liquid surfaces; monolayers and thin films; tribology; flow in unsaturated porous media; applications to drying, mining, and environmental cleanup.

M. Douglas LeVan (Ph.D., Univ. of California, Berkeley)
Fixed-bed adsorption; adsorption equilibria; adsorption processes (pressure-swing adsorption, temperature-swing adsorption, adsorptive refrigeration); process design.

John A. Roth (Ph.D., Louisville)
Physical-chemical wastewater treatment; hazardous waste management; corrosion mechanisms in microcircuitry.

Karl B. Schnelle, Jr. (Ph.D., Carnegie Mellon)
Environmental dispersion modeling; use of natural gas in atmospheric pollution control; supercritical extraction of toxic materials in the environment.

Robert D. Tanner (Ph.D., Case Western Reserve)
Biochemical engineering; effect of light on yeast growth and protein secretion; aerated solid fermentation fluidized bed processes; bubble and aerosol fractionation of proteins.
“For here we are not afraid to follow the truth, no matter where it shall lead . . .”

Thomas Jefferson
Founder, University of Virginia

---

Giorgio Carta, Ph.D.
University of Delaware
Absorption, ion exchange, biochemical engineering

Robert J. Davis, Ph.D.
Stanford University
Heterogeneous catalysis, characterization of metal clusters, reaction kinetics

Erik J. Fernandez, Ph.D.
University of California, Berkeley
Purification of biological molecules, transport

Roseanne M. Ford, Ph.D.
University of Pennsylvania
Bioremediation, bacterial migration (chemotaxis)

John L. Gainer, Ph.D.
University of Delaware
Mass transfer including biomedical applications, biochemical engineering

Andrew C. Hillier, Ph.D.
University of Minnesota
Electrochemistry and electrochemical engineering, surface science, materials synthesis and characterization

John L. Hudson, Ph.D.
Northwestern University
Reaction system dynamics, chaos and pattern formation, electrochemistry

Donald J. Kirwan, Ph.D.
University of Delaware
Biochemical engineering, mass transfer, crystallization

Matthew Neurock, Ph.D.
University of Delaware
Computational heterogeneous catalysis, molecular reaction engineering, kinetics of complex reaction systems

John P. O’Connell, Ph.D.
University of California, Berkeley
Statistical thermodynamics with applications to physical and biological systems

---

To receive application materials and further information, please write to

Graduate Admissions Coordinator
Department of Chemical Engineering
Thornton Hall
University of Virginia
Charlottesville, VA 22903-2442
Phone (804) 924-7778
E-mail: ceadmis@virginia.edu
Catch the Excitement!

Chemical Engineering at Virginia Tech

Catalysis

Artificial Intelligence

Surface Science

Polymers

Green Engineering

Biotechnology

William L. Conger, Professor and Department Head
Ph.D., University of Pennsylvania
Department Administration

Donald G. Baird, The Harry C. Wyatt Professor
Ph.D., University of Wisconsin
Polymer Processing and non-Newtonian Fluid Mechanics

David F. Cox, Associate Professor
Ph.D., University of Florida
Catalysis, Ultrahigh Vacuum Surface Science

Richey M. Davis, Associate Professor
Ph.D., Princeton University
Physical Chemistry and Rheology of Colloids and Polymer Solutions

Kimberly E. Forsten, Assistant Professor
Ph.D., University of Illinois
Computational Bioengineering and Tissue Engineering

Y.A. Liu, The Frank C. Vilbrandt Professor
Ph.D., Princeton University
Artificial Intelligence and Green Engineering Design

Eva Marand, Assistant Professor
Ph.D., University of Massachusetts
Transport through Polymer Membranes, Polymer Spectroscopy

S. Ted Oyama, Professor
Ph.D., Stanford University
Heterogeneous Catalysis and New Materials

Len Peters, Professor
Vice Provost/Research & Dean/Graduate School
Ph.D., University of Pittsburgh
Atmospheric Transport

Peter R. Rony, Professor
Ph.D., University of California, Berkeley
Instrumentation

William H. Velander, Professor
Ph.D., Pennsylvania State University
Transgenic Livestock Bioreactors & Immunopurification of Therapeutics, Biosensors

Garth L. Wilkes, The Fred W. Bull Professor
Ph.D., University of Massachusetts
Structure-Property Behavior of Polymeric Materials

For further information, contact the

Department of Chemical Engineering, Virginia Tech
133 Randolph Hall, Blacksburg, VA 24061-0211
Telephone (540) 231-6631 • Fax (540)231-5022
http://www.eng.vt.edu/eng/che/
e-mail: Dianec@vt.edu
• Vigorous research program
• Excellent physical facilities
• Financial support for all full-time graduate students
• 60 graduate students from 30 universities and 20 states
• 15 students from foreign countries

Graduate students and faculty enjoy a fine esprit de corps in a stimulating and supportive research environment. Seattle, The Emerald City, provides outstanding cultural opportunities and unparalleled outdoor activities throughout the year.

---

**Chemical Engineering Faculty • Research Areas**

**Materials**
- G. Graham Allan (Joint), Ph.D., D.Sc., Glasgow
- John C. Berg, Ph.D., California (Berkeley)
- J.W. Rogers, Jr., Ph.D., Texas (Austin)
- Daniel T. Schwartz, Ph.D., California (Davis)
- James C. Seferis, Ph.D., Delaware
- Eric M. Stuve, Ph.D., Stanford

**Biochemical Engineering and Bioengineering**
- Albert L. Babb, Ph.D., Illinois
- François Baneyx, Ph.D., Texas (Austin)
- Michael W. Chang (Adjunct), Ph.D., Washington; M.D., Texas
- Thomas A. Horbett (Joint), Ph.D., Washington
- Mary E. Lidstrom, Ph.D., Wisconsin
- Buddy D. Ratner (Joint), Ph.D., Brooklyn Polytechnic

**Environmental Technology**
- E. James Davis, Ph.D., Washington
- Barbara Krieger-Brockett, Ph.D., Wayne State

**Computers and Process Control**
- Bruce A. Finlayson, Ph.D., Minnesota
- Bradley R. Holt, Ph.D., Wisconsin
- N. Lawrence Ricker, Ph.D., California (Berkeley)

**Transport Phenomena and Physics**
- René M. Overney, Ph.D., Basel, Switzerland
- Lewis E. Wedgewood, Ph.D., Wisconsin

Graduate Admissions, University of Washington
Department of Chemical Engineering
Box 351750
Seattle, Washington 98195-1750
Phone: (206) 543-2250 Fax: (206) 543-3778
E-mail: grad.admissions@cheme.washington.edu
Web Page: http://weber.u.washington.edu/~chemeng/
Here at Washington State University, we are proud of our graduate program, and of our students. For a department of this size, the range of faculty interests is very broad. Students choose research projects of interest to them, then have the opportunity—and responsibility—to make an individual contribution.

FACULTY AND RESEARCH INTERESTS

C. F. Ivory (Ph.D., Princeton): bioseparations, including electrophoresis, electrochromatography and field flow fractionation.

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

K. C. Liddell (Ph.D., Iowa State University): electrodeposition of magnetic recording materials; environmental applications of supercritical fluid separations; mineral and electrode kinetics; mathematical models for reactive flow.

R. Mahalingam (Ph.D., University of Newcastle-upon-Tyne): multiphase reactors, aerosols, air toxics, hazardous wastes, fossil energy conversion, polymer thin films, process development and design.

R. C. Miller (Ph.D., University of California, Berkeley): thermodynamic properties of natural gases and liquefied petroleum gases; thermophysical properties of cryogenic liquids; environmentally compatible refrigerants.

J. N. Petersen (Ph.D., Iowa State University): bioremediation of chlorinated solvents and metal ions, mathematical modeling of in-situ bioremediation and bioprocessing operations.

B. M. Peyton (Ph.D., Montana State University): process modification, extremophilic bioprocessing, in-situ bacterial transport, bioremediation/bioprocessing of heavy metals, biofilm systems.

W. J. Thomson (Ph.D., University of Idaho): kinetics of solid state reactions, development of solid acid and perovskite membrane catalysts, chemical reaction engineering.

B. J. Van Wie (Ph.D., University of Oklahoma): membrane biosensors, kinetics and reactor design for blood chemistry analysis, mammalian tissue cultures.

R. L. Zollars (Ph.D., University of Colorado): colloidal phenomena, solid entrainment in flowing liquids, polymer reactor design, chemical reaction engineering.

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. B. J. Van Wie, Graduate Coordinator, Department of Chemical Engineering, Washington State University, Pullman, WA 99164-2710
509/335-4332 or 509/335-4103
chedept@che.wsu.edu
GRADUATE STUDY IN CHEMICAL ENGINEERING
MASTER'S AND DOCTORAL PROGRAMS

• Faculty and Research Areas •

M. Al-Dahhan Chemical Reaction Engineering, Multiphase Reactors, Mass Transfer, Process Engineering

M. P. Dudukovic Chemical Reaction Engineering

J. T. Gleaves Heterogeneous Catalysis, Surface Science, Microstructured Materials


J. L. Kardos Composite Materials and Polymer Engineering

B. Khomami Rheology, Polymer and Composite Materials Processing

J. M. McKelvey Polymer Science and Engineering

R. L. Motard Computer Aided Process Engineering, Knowledge-Based Systems

P. A. Ramachandran Chemical Reaction Engineering

R. Sureshkumar Applications of transport processes involving complex polymeric and colloidal fluids

C. Thies Biochemical Engineering, Microencapsulation

J. Turner Environmental Reaction Engineering, Air Quality Policy and Analysis, Air Pollution Control

For Information Contact

Graduate Admissions Committee • Washington University
Department of Chemical Engineering
Campus Box 1198 • One Brookings Drive
St. Louis, Missouri 63130-4899

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.
John Benci, Ph.D., Pennsylvania, 1989
Deformation and fracture of materials ⊕ High temperature mechanical properties of alloys, intermetallic compounds and ceramics

Esin Gulari, Ph.D., Caltech, 1973
Thermodynamics and transport properties of polymer solutions and melts ⊕ Processing of polymers with supercritical fluids ⊕ Light scattering based particle and drop sizing techniques

Yinlun Huang, Ph.D., Kansas State, 1992
Pollution prevention and waste minimization ⊕ Process design and synthesis

Rangaramanujam Kannan, Ph.D., Caltech, 1994 — Dynamics of polymeric systems and interfaces ⊕ Rheo-optical spectroscopy and scattering techniques

Ralph Kummer, Ph.D., John Hopkins, 1966 — Modeling of combined sewer overflows and sediments ⊕ Chemical kinetics ⊕ Computer simulation

Charles Manke, Ph.D., California, Berkeley, 1983 — Polymer processing and rheology ⊕ Molecular dynamics and kinetic theory of polymeric liquids

Guang-Zhao Mao, Ph.D., Minnesota, 1994 — Optoelectronic properties of thin films and crystals ⊕ Self-assembly of polymers and surfactants ⊕ Colloidal stability of waterborne paints ⊕ Real time imaging of surface phenomena at the molecular level

Howard Matthew, Ph.D., Wayne State, 1992 — Tissue engineering and biomaterials ⊕ Artificial organ substitutes

James McMicking, Ph.D., Ohio State, 1961 — Correlation of thermodynamic data

Simon Ng, Ph.D., Michigan, 1985 — Heterogeneous catalysis ⊕ Polymer kinetics ⊕ Spectroscopic and thermal analysis of material surfaces

Sulis Putatunda, Ph.D., IIT Bombay, 1983 — Effects of microstructure on fatigue ⊕ Fracture toughness ⊕ Creep in metals and alloys

Erhard Roth, Ph.D., Michigan, 1959 — Applications of high-powered UV lasers ⊕ Machining of electronic chips ⊕ Diagnostics of internal combustion

Steven Salley, Ph.D., Detroit, 1976 — Biochemical/medical engineering ⊕ Design of artificial organs ⊕ Immobilized enzyme reactors

Gina Shreve, Ph.D., Michigan, 1991 — Environmental and biochemical applications ⊕ Microbially mediated biotransformations

Paul VanTassel, Ph.D., Minnesota, 1993 — Shape selective catalysis ⊕ Protein adsorption and bioseparations

Contact:
Charles W. Manke, Jr., Professor; Graduate Advisor, Materials Science and Eng. • cmanke@cheml.eng.wayne.edu
Yinlun Huang, Assistant Professor; Graduate Advisor, Chemical Engineering • yahunag@cheml.eng.wayne.edu
West Virginia University

M.S. and Ph.D. Programs in Chemical Engineering

RESEARCH AREAS
Catalysis and Reaction Engineering
Polymer Rheology • Multi-Phase Processing
Phase Equilibria • Fluidization
Biomedical Engineering
Particle Science • Carbon Products
Surface and Colloid Phenomena
Advanced Process Development
Biochemical Engineering

Eung H. Cho  
(University of Utah)
Eugene V. Cilento, Chairman  
(University of Cincinnati)
Dady B. Dadyburjor  
(University of Delaware)
Rakesh K. Gupta  
(University of Delaware)
Hisashi O. Kono  
(Kyushu University)
Edwin L. Kugler  
(Johns Hopkins University)
Aubrey L. Miller  
(Illinois Institute of Technology)
Joseph A. Shaeiwitz  
(Carnegie-Mellon University)
Peter G. Stansberry  
(Pennsylvania State University)
Alfred H. Stiller  
(University of Cincinnati)
Charter D. Stinespring  
(West Virginia University)
Richard Turton  
(Oregon State University)
Ray Y. K. Yang  
(Princeton University)
John W. Zondlo  
(Carnegie-Mellon University)

For Application Information, Write
Professor Richard Turton • Graduate Admission Committee  
Department of Chemical Engineering • P.O. Box 6102  
West Virginia University • Morgantown, West Virginia 26506-6102
A tradition of excellence in Chemical Engineering

For further information about graduate study in chemical engineering, write:
The Graduate Committee
Department of Chemical Engineering
University of Wisconsin–Madison
1415 Engineering Drive
Madison, Wisconsin 53706-1691
http://www.engr.wisc.edu/che

- **Douglas C. Cameron**
  Biotechnology, metabolic engineering

- **Thomas W. Chapman**
  Electrochemical reaction engineering

- **Juan de Pablo**
  Molecular thermodynamics, statistical mechanics, polymer physics

- **James A. Dumesic**
  Kinetics and catalysis, surface chemistry

- **Michael D. Graham**
  Fluid mechanics, applied and computational mathematics

- **Charles G. Hill, Jr.**
  Immobilized enzyme technology, photocatalysis, kinetics and catalysis, composite wood products, membrane separations

- **Sangtae Kim (Chairman)**
  Fluid mechanics and rheology, protein dynamics, parallel computing

- **Daniel J. Klingenberg**
  Colloid science, complex fluids, suspension rheology

- **Thomas F. Kuech**
  Semiconductor and materials processing, solid-state and electronic materials, thin films

- **Regina M. Murphy**
  Biomedical engineering, protein-protein interactions, targeted drug delivery

- **Paul F. Nealey**
  Polymers, surface and interfacial phenomena, nanofabrication

- **James B. Rawlings**
  Process modeling, dynamics and control, particle technology, crystallization

- **W. Harmon Ray**
  Reaction engineering, polymerization processes, process dynamics and control

- **Thatcher W. Root**
  Surface chemistry, catalysis, solid-state NMR, MRI, and protein chromatography

- **Ross E. Swaney**
  Process design, synthesis, modeling, and optimization
Graduate Studies in Chemical Engineering

Areas of Research:

Advanced Materials
- Inorganic Membranes
- Molecular Sieve Zeolites
- Nanostructured Materials
- Diamond Thin Films

Biochemical Engineering
- Bioreactor Analysis
- Bioprocesses

Catalysis and Reaction Engineering
- Adsorption and Transport in Porous Media
- Heterogeneous and Homogeneous Catalysis
- Zeolite Catalysis
- Environmental Catalysis

Environmental Engineering
- Aerosol Dynamics
- Nucleation and Phase Transitions
- Waste Reduction Technology

Faculty:

William M. Clark • Ph.D., Rice
David DiBiasio • Ph.D., Purdue
Anthony G. Dixon • Ph.D., Edinburgh
Yi Hua Ma • Sc.D., MIT
William R. Moser • Ph.D., MIT
Fabio Ribeiro • Ph.D., Stanford University
Karen McNamara Rutledge • Ph.D., MIT
Robert W. Thompson • Ph.D., Iowa State
Barbara E. Wyslouzil • Ph.D., CalTech
Alvin H. Weiss, Emeritus • Ph.D., U. Pennsylvania

The Central New England Area:

WPI is situated on a 62-acre hilltop site in a residential area of Worcester, Massachusetts, New England's second largest city and a leading cultural, educational, and entertainment center. It is a one-hour drive from Boston and only two hours from the beaches of Cape Cod and the ski slopes and hiking trails of Vermont and New Hampshire.

For further information contact:

Graduate Coordinator
Chemical Engineering Department
Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609-2280
or for a closer look at WPI, visit our World Wide Web site at http://www.wpi.edu
We offer exciting opportunities for research in many processing areas, especially energy related and environmental control technology development. In recent years we have developed enhanced oil recovery, clean coal, solid waste utilization, and advanced gas clean-up technologies up to bench scale levels. Currently we are working with industry to construct and operate pilot units of these technologies. This will provide excellent opportunities for students to obtain hands-on experience on industrial projects. Also, research has been conducted in the areas of kinetics, catalysis, adsorption, extraction, computer modeling, coal processing, and enhanced oil recovery.

The Western Coal Consortium has been established by the Chemical and Petroleum Engineering Department with western coal producers and utilities. The Western Coal Consortium, Enhanced Oil Recovery Institute, NSF/EPSCoR and DOE/EPSCoR Programs provide excellent financial aid packages to graduate students.

The University of Wyoming is located in Laramie, Wyoming at an elevation of 7200 feet. The town is surrounded by state and national parks which allow for beautiful year-round outdoor activities. The nearby Snowy Range mountains provide ideal sources of recreation for mountain and rock climbing, skiing, fishing, and hunting.

Graduates of any accredited chemical and petroleum engineering engineering programs are eligible for admission, and the department offers both M.S. and Ph.D. chemical and petroleum accredited programs. Financial aid is available, and all recipients receive full fee waivers.

For more information contact
Dr. David O. Cooney, Coordinator for Graduate Studies • Chemical & Petroleum Engineering Department
University of Wyoming • P. O. Box 3295 • Laramie, WY 82071-3295
Telephone (307) 766-2500
Eric Altman, Ph.D. Pennsylvania
Marshall Grant, Ph.D. Princeton
Gary L. Haller, Ph.D. Northwestern
Csaba G. Horváth, Ph.D. Frankfurt
Michael Loewenberg, Ph.D. Cal Tech
Lisa D. Pfefferle, Ph.D. Pennsylvania
Daniel E. Rosner, Ph.D. Princeton
John Y. Walz, Ph.D. Carnegie Mellon

Adjunct Professors
• F. Peter Boer
• Donald M. Crothers
• Alexander V. Neimark
• Robert Weber
• L. Lee Wikstrom

Joint Appointments
• Thomas Graedel (School of Forestry & Environmental Studies)
• Kurt Zilm

Lecturers
• Bela G. Lipták
• Joseph J. Levitzky

Yale University
P. O. Box 208286
New Haven, Ct 06520-8286
Phone: (203) 432-2222 • FAX: (203) 432-7232
http://www.yale.edu/yaleche

Aggregation, Clustering
Biochemical Engineering
Catalysis
Chemical Reaction Engineering
Chemical Vapor Deposition
Chromatography
Combustion
Environmental ChE Science
Enzyme Technology
Fine Particle Technology
Heterogeneous Kinetics
Interfacial and Colloidal Phenomena
Materials Synthesis and Processing
Multiphase Transport Phenomena
Separation Science and Technology
Statistical Thermodynamics
Supercritical Fluid Phenomena
Surface Science

Chemical Engineering Education
BRIGHAM YOUNG UNIVERSITY

Graduate Studies in Chemical Engineering

M.S. and Ph.D. Degree Programs

Faculty and Research Interests

Calvin H. Bartholomew (Stanford) • kinetics and catalysis
Merrill W. Beckstead (Utah) • propellant combustion, modeling
Thomas H. Fletcher (BYU) • coal pyrolysis and combustion
Hugh B. Hales (MIT) • reservoir engineering
John H. Harb (Illinois) • coal combustion, electrochemical engineering
William C. Hecker (UC Berkeley) • kinetics and catalysis
Paul O. Hedman (BYU) • energy, combustion, chemical propulsion
John L. Oscarson (Michigan) • calorimetry and thermodynamics
William G. Pitt (Wisconsin) • materials science
Richard L. Rowley (Michigan State) • thermophysical properties
L. Douglas Smoot (Washington) • fossil energy and combustion
Kenneth A. Solen (Wisconsin) • biomedical engineering
Ronald E. Terry (BYU) • engineering education, process control
W. Vincent Wilding (Rice) • thermodynamics, environmental engineering

Financial Support Available

For further information
See our website at: http://et.byu.edu/~che/CheDept.html
Contact: Graduate Coordinator • Dept. of Chemical Engineering • P.O. Box 24100
Brigham Young University • Provo, UT 84602 • (801) 378-2586

Department of Chemical and Bio-Resource Engineering

University of British Columbia

Vancouver, Canada

The UBC Department of Chemical and Bio-Resource Engineering offers three graduate degrees in the Chemical Engineering Program: Master of Applied Science (M.A.Sc.), Master of Engineering (M.Eng.), and Doctor of Philosophy (Ph.D.). Thesis topics are available in the fields of faculty research that include:

- Pulp and Paper Research
- Biochemical/Biomedical Engineering
- Biotechnology
- Electrochemical Engineering
- Environmental Engineering
- Reaction Engineering
- Kinetics and Catalysis
- Thermodynamics
- Polymer Rheology
- Process Control
- Transport Phenomena

Financial Aid: All students admitted to the graduate programs leading to the M.A.Sc. or Ph.D. degrees receive at least a minimum level of financial support regardless of citizenship. This amount is approximately $15,000/year and is intended to be sufficient to cover expenses for the year. This financial assistance is in the form of external fellowships or research assistantships. Research assistantships are provided by the professor under whose supervision the student is doing his or her thesis. Teaching assistantships also are available (up to approximately $2,000/year).

For further information visit our web site at http://www.chem.ubc.ca

The Department operates joint research programs at the M.A.Sc. and Ph.D. levels with the UBC Biotechnology Laboratory and the Pulp and Paper Research Institute of Canada (PAPRICAN) in areas of common interest. An interdisciplinary M.Eng degree in Pulp and Paper Engineering is also offered by the Department in collaboration with PAPRICAN, and the Department plays a direct role in the M.Eng. degree program in Fire Protection Engineering

Application forms can be obtained from
web@chem.ubc.ca

or from

Graduate Student Secretary • Department of Chemical Engineering
University of British Columbia • 2216 Main Mall
Vancouver, B.C., Canada V6T 1Z4
Tel: (604) 822-3238 Fax: (604) 822-6003
CLEVELAND STATE UNIVERSITY

Graduate Studies in Chemical Engineering
M.Sc. and D.Eng. Programs

RESEARCH AREAS

- Materials Synthesis and Processing
- Process Modeling, Simulation
- Adsorption Processes
- Computation Fluid Dynamics and Combustion
- Environmental Pollution Control
- Surface Phenomena and Mass Transfer
- Thermodynamics and Fluid Phase Equilibria
- Transport Phenomena, Fluid Mechanics
- Tribology
- Zeolites: Synthesis, Sorption, Diffusion
- Artificial Pancreas Design

FACULTY

- G. A. Coulman (Case Reserve)
- N. H. Dural (Missouri-Columbia)
- R. P. Elliott (Illinois Inst. of Tech.)
- J. E. Gatica (SUNY at Buffalo)
- B. Ghorashi (Ohio State)
- E. S. Godleski (Oklahoma State)
- E. E. Graham (Northwestern)
- J. M. Belovich (Michigan)
- D. B. Shah (Michigan State)
- O. Talu (Arizona State)
- S. N. Tewari (Purdue)

Cleveland State University has 18,000 students enrolled in its academic programs. It is located in the center of the city of Cleveland, with many outstanding cultural and recreational opportunities nearby.

FOR FURTHER INFORMATION, WRITE TO

Graduate Program Coordinator • Department of Chemical Engineering
Cleveland State University • Cleveland, OH 44115

Telephone (216) 687-2569 • e-mail: cheme@opus.csuohio.edu • www: http://www.csuohio.edu/chemical_engineering/

COLUMBIA UNIVERSITY

NEW YORK, NEW YORK 10027

Graduate Programs in Chemical Engineering, Applied Chemistry, and Bioengineering

Faculty and Research Areas

<table>
<thead>
<tr>
<th>Name</th>
<th>Research Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>H. Y. CHEH</td>
<td>Electrochemical Engineering</td>
</tr>
<tr>
<td>P. DUBY</td>
<td>Electro Chemistry</td>
</tr>
<tr>
<td>C. J. DURNING</td>
<td>Polymer Physical Chemistry</td>
</tr>
<tr>
<td>C. C. GRYTE</td>
<td>Polymer Science, Separation Processes, Pharmaceutical Engineering</td>
</tr>
<tr>
<td>C. HARRIS</td>
<td>Solid Processing</td>
</tr>
<tr>
<td>E. F. LEONARD</td>
<td>Biomedical Engineering, Transport Phenomena</td>
</tr>
<tr>
<td>B. O’SHAUGHNESSY</td>
<td>Polymer Physics</td>
</tr>
<tr>
<td>P. SOMASUNDARAN</td>
<td>Colloid and Surface Science</td>
</tr>
<tr>
<td>J. L. SPENCER</td>
<td>Applied Mathematics, Chemical Reactor Engineering</td>
</tr>
<tr>
<td>N. THEMELIS</td>
<td>Earth Engineering</td>
</tr>
<tr>
<td>J. THOMAS</td>
<td>Biomolecular Engineering</td>
</tr>
<tr>
<td>A. C. WEST</td>
<td>Electrochemical Engineering, Mathematical Modeling</td>
</tr>
</tbody>
</table>

Financial Assistance is Available

For Further Information, Write
Chairman, Graduate Committee
Department of Chemical Engineering
Columbia University
New York, NY 10027
(212) 854-4453

Chemical Engineering Education
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH COLLEGE
Ph.D. and M.S. in Engineering Sciences with Specialization in

Biochemical Engineering

Research Fields

• Advanced bioreactors
• Biomass conversion and renewable energy
• Environmental biotechnology
• Enzyme kinetics
• Evolutionary biotechnology
• Metabolic engineering

Primary Faculty

Alvin O. Converse
Ph.D., Delaware

Lee R. Lynd
D.E., Dartmouth
Presidential Young Investigator Award

John Yin
Ph.D., Berkeley
Presidential Early Career Award

Contact: Director of Admissions • Biotechnology and Biochemical Engineering Program • Thayer School of Engineering • Dartmouth College • Hanover, NH 03755

DREXEL UNIVERSITY

M.S. and Ph.D. Programs in Chemical Engineering and Biochemical Engineering

FACULTY

• R. A. Cairncross
• D. R. Coughanour
• E. D. Grossmann
• Y. H. Lee
• A. M. Lowman
• S. P. Meyer
• Y. T. Shah
• M. Soroush
• R. Mutharasan
• C. B. Weinberger
• M. A. Wheatley

RESEARCH AREAS

Biochemical Engineering • Biomedical Engineering • Reactor Engineering • Environmental Engineering • Polymer Processing
Process Control and Dynamics • Rheology and Fluid Mechanics
Semiconductor Processing • Systems Analysis and Optimization
Thermodynamics and Process Energy Analysis

CONSIDER

• High faculty / student ratio • Excellent facilities • Outstanding location for cultural activities and job opportunities

WRITE TO:
Dr. Masoud Soroush
Department of Chemical Engineering
Drexel University • Philadelphia, PA 19104

Fall 1997
University of Idaho

Chemical Engineering M.S. and Ph.D. Programs

FACULTY

W. ADMASSU  Synthetic Membranes for Gas Separations, Biochemical Engineering with Environmental Applications

T. E. CARLESON  Mass Transfer Enhancement, Chemical Reprocessing of Nuclear Wastes, Bioseparation


R. A. KORUS  Polymers, Biochemical Engineering

J. Y. PARK  Chemical Reaction Analysis and Catalysis, Laboratory Reactor Development, Thermal Plasma Systems

J. J. SCHELDОРF  Heat Transfer, Thermodynamics

M. VON BRAUN  Hazardous Waste Site Analysis, Computer Mapping

The department has a highly active research program covering a wide range of interests. The northern Idaho region offers a year-round complement of outdoor activities including hiking, white water rafting, skiing, and camping.

A wide range of fellowships and assistantships is available.

FOR FURTHER INFORMATION AND APPLICATION WRITE

Graduate Advisor
Chemical Engineering Department
University of Idaho
Moscow, Idaho 83844-1021

Imperial College of Science, Technology, and Medicine

University of London

Department of Chemical Engineering and Chemical Technology

and the Interdisciplinary Research Center (IRC) in Process Systems Engineering

Applications are invited for postgraduate studies for the following degrees:

MSc in Advanced Chemical Engineering or Process Systems Engineering • One-year MSc courses combining a research project with 4-7 taught modules chosen from a comprehensive list of technical and business studies courses. EPSRC grants are available to qualified students.

PhD in Chemical Engineering • This is a three-year research degree that may be undertaken in the Department and/or the IRC. EPSRC grants and other forms of financial support are available.

The Department adopts an interdisciplinary approach to research with interests ranging from fundamentals to practical applications.

Current fields of RESEARCH include:

Applied Catalysis & Reaction Engineering, Biotechnology, Separations & Environmental Applications, Combustion, Mechanics and Thermophysics of Fluids, Multiphase Flow, Particle Technology, Polymers, Process Systems Engineering

The teaching and research laboratories are exceptionally well equipped and fully backed by comprehensive technical services. First-class computing facilities are provided in both the Department and the IRC.

For an information pack and application form, please contact:

Dr. N. Shah, Department of Chemical Engineering and Chemical Technology, Imperial College, London SW7 2BY
Tel: +44-171-5946621 • Fax: +44-171-5946606 • E-mail: n.shah@ic.ac.uk • http://viking.ce.ic.ac.uk
LAMAR UNIVERSITY

GRADUATE STUDY IN CHEMICAL ENGINEERING

Master of Engineering  ■  Master of Engineering Science  ■  Master of Environmental Engineering  ■  Doctor of Engineering

FACULTY

• D. H. CHEN  
  (Ph.D., Oklahoma State University)
• J. R. HOPPER  
  (Ph.D., Louisiana State University)
• T. C. HO  
  (Ph.D., Kansas State University)
• K. Y. LI  
  (Ph.D., Mississippi State University)
• C. L. YAWS  
  (Ph.D., University of Houston)

RESEARCH AREAS

• Computer Simulation, Process Dynamics and Control  
  • Heterogeneous Catalysis, Reaction Engineering  
  • Fluidization, Incineration  
• Transport Properties, Mass Transfer, Gas-Liquid Reactions  
  • Computer-Aided Design  
• Thermodynamic Properties, Cost Engineering, Photovoltaics  
  • Air Pollution, Bioremediation, Waste Minimization  
  • Hazardous Waste Management, Pollution Prevention

For further information, please write
Graduate Admissions Chairman • Department of Chemical Engineering • Lamar University • P. O. Box 10053 • Beaumont, TX 77710

An equal opportunity/affirmative action university.

Department of Chemical Engineering

3-Year PhD & 2-Year MPhil in CHEMICAL ENGINEERING

Major research areas:
  Carbon Research  
    Professor John Patrick
  Environmental Process Engineering  
    Professor Michael Streat
  Food Engineering & Biotechnology  
    Dr George Hall
  Particle Technology and Separation Processes  
    Professor Richard Wakeman
  Plant Engineering  
    Dr Andy Rushton
  Reaction Engineering  
    Professor Brian Brooks
  Solid-Fluid Systems  
    Professor Bryan Buffham

A 12-month modular course starting in October each year, comprising four taught courses chosen from a range of advanced subjects, followed by a research project

Partial funding available.

Contact: Dr. Tony Ward

SABBATICAL VISITORS WELCOME

Write, telephone, or email for more information to Department of Chemical Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, England

Tel: +44 1509 222532  Fax: +44 1509 223923  email: cgadmin@Lboro.ac.uk

Fall 1997

20 academic staff 50 postgraduates 
280 undergraduates the biggest campus in Britain 2 hours from London by train

One of the top-rated Chemical Engineering Departments in the UK
LOUISIANA TECH UNIVERSITY
Master of Science and Doctor of Engineering Programs

The Department of Chemical Engineering at Louisiana Tech University offers a well-balanced graduate program for either the Master’s or Doctor of Engineering degree. Students are pursuing research in Alternative Fuels, Biotechnology, Chemical Process Hazards and Fire Safety, Micro Reactor Design, Nuclear Process Environmental Effects, and Process Simulation and Design.

University of Louisville
Chemical Engineering M.S. and Ph.D. Programs

RESEARCH AREAS
Biotechnology • Catalysis • Polymers • Polymer Processing
Process Control • Separations • The Environment • Molecular Modeling
Waste Management • CVD of Diamond Films

Facilities include state-of-the-art Materials Research, Biotechnology and Food Engineering Laboratories

For More Information, Contact
Dr. Bill Elmore
Assoc. Professor & Chairman
Chemical Engineering Louisiana Tech University Ruston, Louisiana 71272
(318) 257-2483
belmore@engr.latech.edu

FACULTY
Dermot J. Collins
Pradeep B. Deshpande
Marvin Fleischman
Walden L. S. Laukhuf
Thomas R. Hanley
Dean O. Harper
Raul Miranda
Hugh T. Spencer
Mahendra Sunkara
James C. Watters

Competitive fellowships and assistantships are available to qualified students.
Write to: Graduate Student Advisor • Chemical Engineering Department
University of Louisville • Louisville, KY 40292
Inquiries can be addressed via Electronic Mail to: DOHARP01@ULKYVM.LOUISVILLE.EDU
For further information, please contact

Dr. T. E. Marlin
Department of Chemical Engineering
McMaster University
Hamilton, Ontario, Canada L8S 4L7
Monash offers programs of study and research leading to MSc and PhD in chemical engineering. At Monash, you'll enjoy first-rate facilities, a wide choice of research areas, and the opportunity to work closely with industry through the Australian Pulp and Paper Institute, the Dairy Process Engineering Center, and the Cooperative Research Centers for New Technologies for Power Generation from Low-Rank Coals, and Hardwood Fibre and Paper Science.

**RESEARCH AREAS**

- Particle Technology
- Pulp Technology
- Chemical Reaction Engineering
- Transport Phenomena
- Extractive Metallurgy and Mineral Processing
- Food Engineering
- Waste Treatment and Water Purification
- Brown Coal Utilisation
- Paper Making
- Heterogeneous Catalysis
- Adsorption Engineering
- Rheology
- Biochemical Engineering
- Process Design and Economics

The Faculty

- T. Sridhar
- J.R.G. Andrews
- W.J. Batchelor
- D.J. Brennan
- R.E. Johnston
- F. Lawson (honorary)
- C-Z. Li
- J.F. Mathews
- K.L. Nguyen
- R.S. Nicol
- W.E. Olbrich
- I.H. Parker
- O.E. Potter (emeritus)
- I.G. Prince
- M.J. Rhodes
- C. Tiu
- P.H. T. Uhlherr
- P.A. Webley

Department of Chemical Engineering

FOR FURTHER INFORMATION CONTACT
Graduate Studies Coordinator, Department of Chemical Engineering, Monash University, Clayton Victoria 3168 Australia. Fax +61 3 9905 5686
e-mail: prince@eng.monash.edu.au
http://www.monash.edu.au

New Mexico State University

Master of Science and Doctor of Philosophy in Chemical Engineering

**Major Research Areas**

- Advanced Materials
- Biochemical Engineering
- Computer-Aided Engineering
- Engineering Design
- Environmental Engineering
- Food Engineering
- Therodynamics
- Transport Phenomena

**Faculty**

- Paul K. Andersen, Associate Professor
  PhD, University of California, Berkeley
- Ron Bhada, Professor, Head & Associate Dean
  PhD, University of Michigan
- Sarah Harcum, Assistant Professor
  PhD, University of Maryland
- Richard Long, Associate Professor
  PhD, Rice University
- Martha Mitchell, Assistant Professor
  PhD, University of Minnesota
- Stuart Munson-McGee, Associate Professor
  PhD, University of Delaware
- David Rockstraw, Assistant Professor
  PhD, Oklahoma University
- Joe Creed, Assistant Dean
  MS, New Mexico State University
- Francisco Del Valle, College Professor
  PhD, Massachusetts Institute of Technology
- John Patton, Professor Emeritus
  PhD, Oklahoma State University
- Rudi Roubicek, Professor Emeritus
  PhD, Technical University of Prague
- Edward Thode, Professor Emeritus
  PhD, Massachusetts Institute of Technology
- D. Bruce Wilson, Professor Emeritus
  PhD, Princeton University

Application and Additional Information

P.O. Box 30001, MSC 3805
NMSU
Las Cruces, NM 88003
e-mail: gradinfo@chemeng.nmsu.edu
WWW: http://chemeng.nmsu.edu/

New Mexico State University is an Equal Opportunity Affirmative Action Employer
THE UNIVERSITY OF NEW SOUTH WALES
Sydney, Australia

POSTGRADUATE STUDY IN CHEMICAL ENGINEERING AND INDUSTRIAL CHEMISTRY

• RESEARCH AREAS •

Air and Water Pollution Control
Battery Research and Development
Catalysis and Reactor Design
Characterization and Optimization in Minerals Processing
Chemical Separations
Electrochemistry
Fuel Technology
Glass Technology
High Temperature Materials
Membrane Technology
Particle Technology
Petroleum Engineering
Polymer Science and Engineering
Particle Technology
Process Control and Microprocessor Applications
Pyrometallurgical Reactor Modeling
Solvent Extraction
Supercritical Fluids
Two-Phase Flow
Waste Processing

This is the largest Chemical Engineering School in Australia, with 23 academic staff, over 400 undergraduates, and about 80 postgraduates. The School is well supplied with equipment and is supported by research grants from Government and Industry. The main departments of Chemical Engineering and Industrial Chemistry offer course work and research work leading to M.Sc., M.E., and Ph.D. degrees. The breadth and depth of experience available leads to the production of well-rounded graduates with excellent job potential. International recognition is only one of the many benefits of a degree from UNSW.

The University is the largest in Australia and is located between the center of Sydney and the beaches. The cosmopolitan city and the wide range of outdoor activities make life very pleasant for students, and people from America, Europe, Africa, and the East feel welcome from their first arrival.

For further information concerning specific research areas, facilities, and financial conditions, write to:
Professor R.P. Chaplin
School of Chemical Engineering & Industrial Chemistry
University of New South Wales • Sydney 2052, Australia

The department offers Masters of Science in Engineering degree and also participates in the cooperative PhD program with the North Carolina State University. Research emphasizes both experimental and theoretical work in areas of national interest, with modern research equipment available for most areas of studies. The department is a major participant in a $3.35 million, six-year project recently funded by the Air Force Office of Scientific Research titled “FAST Center for Environmental Remediation, Fate and Transport of Hazardous Chemicals,” with Dr. Kabadi as Project Director. Generous financial assistance is available to all qualified students.

Faculty

- Yusuf G. Adewuyi
  Associate Professor, PhD, University of Iowa
- Shamsuddin Ilias
  Associate Professor, PhD, Queen’s University
- Vinayak N. Kabadi
  Professor, PhD, Pennsylvania State University
- Franklin G. King
  Professor and Chairman, DSc, Stevens Institute of Technology
- Kenneth L. Roberts
  Assistant Professor, PhD, University of South Carolina
- Keith A. Schimmel
  Associate Professor, PhD, Northwestern University
- Gary B. Tatterson
  Professor, PhD, Ohio State University
- Gary L. White
  Assistant Professor, PhD, Michigan State University

For Information and Application, Write to
Graduate Program Coordinator • Department of Chemical Engineering
North Carolina A&T State University • Greensboro, NC 27411
Tel: (910)334-7564 • Fax: (910) 334-7904

Research Areas

- Biochemical Engineering
- Bioremediation
- Catalysis
- Chemical Reaction Engineering
- Coal Research
- Composite Materials
- Computational Fluid Dynamics
- Diffusion through Porous Media
- Environmental Engineering
- Fluid Phase Equilibria
- Interfacial Phenomena
- Membrane Separations/Reactors
- Process Control
- Supercritical Extraction
- Thermodynamics
- Turbulence and Mixing
Northeastern University has educated superior engineers who have contributed significantly to the technological advances of our country.

The Chemical Engineering Department offers full and part-time graduate programs leading to M.S. and Ph.D. degrees. Our programs are designed to provide up-to-date knowledge and skills necessary to keep abreast of today’s changing technology. Courses are offered in the late afternoon and early evening to allow students to advance their academic and professional careers.

RESEARCH AREAS:
• Biochemical Engineering
• Biotechnology
• Catalysis
• Microgravity Materials
• Process Control
• Process Design
• Heat/Mass Transfer
• NASA Center for Advanced Microgravity Materials Processing

FOR INFORMATION WRITE:
Ralph A. Buonopane, Ph.D.
Dept. of Chemical Engineering
Northeastern University
360 Huntington, 342 SN-CEE
Boston, MA 02115

Université d’Ottawa • University of Ottawa

The department offers Graduate Programs leading to M.Eng., M.A. Sc., and Ph.D. degrees in Chemical Engineering and in Environmental Engineering. The faculty conducts fundamental and applied research in a variety of Chemical Engineering and related areas.

Research
• Adsorption • Biochemical Engineering • Biomedical Engineering • Catalysis • Enhanced Oil Recovery • Environmental Engineering • Equations of State • Excess Thermodynamic Properties • Flow Through Porous Media • Gas and Liquid Separations • Interfacial Tension in Oil/Water Systems • Polymer Processing • Polymer Reaction Engineering and Applied Statistics • Reaction Engineering • Rheology and Filtration • Statistical Modeling and Control • Supercritical Fluid Extraction • Synthetic Membranes • Membrane Separation Technologies

Research and Teaching Assistantships are available for qualified graduate students.

Write for more information to:
Université d’Ottawa University of Ottawa
Faculté de génie Faculty of Engineering
Génie chimique Chemical Engineering
161, rue Louis-Pasteur C.P. 450, Succ. A 161 Louis Pasteur St., P.O. Box 450, Stn. A
Ottawa (Ontario) K1N 6N5 Canada Ottawa, Ontario K1N 6N5 Canada


Faculty
• M. Dubé
• Z. Duvnjak
• V. Hornof
• K.J. Kennedy
• W. Kozicki (Emeritus)
• B.C.-Y. Lu (Emeritus)
• R.S. Mann (Emeritus)
• T. Matsuura
• D.D. McLean
• E. Mitsoulis
• G.H. Neale
• H. Sheardown
• D.G. Taylor
• F.H. Tezel
• A.Y. Tremblay

Chemical Engineering Education
Princeton University M.S.E. and Ph.D. Programs in Chemical Engineering

RESEARCH AREAS

Applied Mathematics; Ceramic Materials; Chemical Kinetics; Catalysis; Chemical Reactor/Reaction Engineering; Colloidal Phenomena; Computational Chemistry; Computer Aided Design; Crystallization and Dendritic Growth; Electrohydrodynamics; Environmental Science and Engineering; Flow of Granular Media; Fluid Mechanics; Interfacial Phenomena; Molecular Simulations; Nonlinear Dynamics; Optimization; Polymer Science and Materials; Process Design; Process Control; Process Synthesis; Rheology; Statistical Mechanics; Supercritical Fluids; Surface Science; Thermodynamics and Phase Equilibria

FACULTY


Write to:
Director of Graduate Studies
Chemical Engineering
Princeton University
Princeton, New Jersey 08544-5263

Inquiries can be addressed via Electronic Mail over BITNET to CHEGRAD@PUCC

UNIVERSITY OF RHODE ISLAND

GRADUATE STUDY IN CHEMICAL ENGINEERING

M.S. and Ph.D. Degrees

Applications for financial aid should be received not later than February 1st.

FOR APPLICATIONS, APPLY TO
Chairman, Graduate Committee
Department of Chemical Engineering
University of Rhode Island
Kingston, RI 02881

CURRENT AREAS OF INTEREST

Biochemical Engineering
Biomedical Engineering
Corrosion
Environmental Engineering
Thin Films
Pollution Prevention
Heat and Mass Transfer
Metallurgy and Ceramics
Multiphase Flow
Phase Change Kinetics
Process Simulation
Separation Processes
Surface Phenomena
Transport Phenomena
RESEARCH AREAS

- Kinetics and Catalysis
- Process Control
- Polymers
- Thermodynamics
- Transport Phenomena
- Biotechnology
- Pollution Control

FACULTY

- C. F. Abegg, Ph.D., Iowa State
- R. S. Artigue, D.E., Tulane
- W. B. Baratuci, Ph.D., Case Western Reserve
- J. A. Caskey, Ph.D., Clemson
- W. B. Baratuci, Ph.D., Case Western Reserve
- M. H. Hariri, Ph.D., Manchester
- C.W-T. Lee, Ph.D., Cornell
- S. Leipziger, Ph.D., I.I.T.
- N. E. Moore, Ph.D., Purdue

FOR INFORMATION WRITE

Dr. Carl Abegg • Department Graduate Advisor
Chemical Engineering Department
Rose-Hulman Institute of Technology • Terre Haute, IN 47803-3999
UNIVERSITY OF SOUTHERN CALIFORNIA

GRADUATE STUDY IN CHEMICAL ENGINEERING

• FACULTY •

W. VICTOR CHANG
(Ph.D., Ch.E., Caltech, 1976) • Physical properties of polymers and composites; adhesion; finite element analysis

IRAJ ERSAGHI
(Ph.D., PTE, Southern Cal, 1972) • Well test analyses of fractured, geothermal, and gas storage reservoirs; reservoir characterization; petrophysical modeling

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, 1982) • Thermodynamics and statistical mechanics; supercritical extraction

RONALD G. MINET
(Ph.D., Ch.E., New York University, 1959) (Adjunct) • Computer aided chemical process and plant design; catalysis; ceramic membranes

CHING-AN PENG
(Ph.D., Ch.E., University of Michigan, 1995) • Biochemical engineering; biotechnology

MUHAMMAD SAHIMI
(Ph.D., Ch.E., Minnesota, 1984) • Transport and mechanical properties of disordered systems; percolation theory and non-equilibrium growth processes; flow, diffusion, dispersion and reaction in porous media

THEODORE T. TSOTSIS
(Ph.D., Ch.E., Illinois, Urbana, 1978) • Chemical reaction engineering; process dynamics and control

IAN A. WEBSTER
(D.Sc., Ch.E., M.I.T., 1984) (Adjunct) • Catalysis and reaction kinetics; transport phenomena, chemical reaction engineering; surface spectroscopy, biochemical engineering

YANIS C. YORTSOS
(Ph.D., Ch.E., Caltech, 1979) • Mathematical modeling of transport processes; flow and transport in porous media

Please write for further information about the program, financial support, and application forms to:

Graduate Admissions
Department of Chemical Engineering
University of Southern California
University Park
Los Angeles, CA 90089-1211

CHEMICAL ENGINEERING AT

STATE UNIVERSITY OF NEW YORK AT BUFFALO

• FACULTY •

P. Alexandridis
R. J. Good
A. Gupta
V. Hlavacek
K. M. Kiser
D. A. Kofke
C. R. F. Lund
T. J. Mountziaris
S. Neelamegham
J. M. Nitsche
E. Ruckenstein
M. E. Ryan
C. J. van Oss
T. W. Weber
S. W. Weber

Adsortion
Applied Mathematics
Biomedical Engineering
Catalysis, Kinetics, & Reactor Design
Ceramics
Design
Electronic Materials
Environmental Engineering

Fluid Mechanics
Polymer Processing & Rheology
Process Control
Reaction Engineering
Separation Processes
Surface Phenomena & Colloids
Thermodynamics
Transport Phenomena

For information and applications, write to: Chairman, Graduate Committee • Department of Chemical Engineering State University of New York at Buffalo • Buffalo, New York 14260-4200
Expand Your World . . .

Syracuse University

Chemical Engineering and Materials Science

FACULTY

- Allen J. Barduhn (Emeritus)
- John C. Heydweiller
- George C. Martin
- Philip A. Rice
- Ashok S. Sangani

- Klaus Schroder (Emeritus)
- James A. Schwarz
- S. Alexander Stern
- Lawrence L. Tavlarides
- Chi Tien (Emeritus)

For information
Dr. George C. Martin
Department of Chemical Engineering and Materials Science
220 Hinds Hall • Syracuse University
Syracuse, NY 13244
(315) 443-2557
ASPIRE TO
NEW HEIGHTS

The University of Utah is the oldest state-run university west of the Missouri River. The University is world-renowned for research activities in medicine, science, and engineering. The graduate Chemical Engineering program offers a number of collaborative, interdisciplinary research opportunities.

The University is located in Salt Lake City, the only metropolitan area in the country which is within 45 minutes of seven major ski areas and within a day's drive of five national parks. Entertainment in the city includes: resident ballet, symphony, and theater organizations; professional sports; and a variety of live music performances in public and private establishments throughout the city.

General areas of research:
- biotechnology
- catalysis
- ceramics processing
- coal technology
- combustion
- computer-aided design
- fossil-fuels conversion
- hazardous waste management
- minerals processing
- molecular modeling
- polymer science and rheology

For information, write
Director of Graduate Studies • Department of Chemical and Fuels Engineering
University of Utah • Salt Lake City, Utah 84112

Graduate Studies in Chemical and Fuels Engineering
UNIVERSITY OF UTAH

For information, visit our web site at • http://www.che.utah.edu or e-mail • David.Bodily@mcc.utah.edu

Fall 1997
Graduate Study in Chemical Engineering

The Department of Chemical Engineering at the University of Waterloo is the largest in Canada offering a wide range of graduate programs. Full-time, part-time, or co-operative (alternating academic and work terms) M.A.Sc. programs are available as both coursework and research options. Full-time, part-time, or co-operative Ph.D. programs are available in all research areas. Financial aid is available in the form of entrance scholarships, research assistantships, and teaching assistantships.

RESEARCH AREAS

- Biochemical engineering and industrial biotechnology
- Chemical kinetics, catalysis and reactor design, energy conversion
- Environmental engineering and pollution control
- Electrochemical engineering
- Flow in porous media and enhanced oil recovery
- Mathematical analysis, statistics, and process control
- Polymer science and engineering, polymer processing
- Transport phenomena

For further information, write or phone

The Associate Chair (Graduate Studies)
Department of Chemical Engineering • University of Waterloo
Waterloo, Ontario, Canada N2L 3G1
Phone (519) 888-4567, ext. 2484 • Fax (519) 746-4979
e-mail at dmuller@cape.uwaterloo.ca
or visit our website at http://cape.uwaterloo.ca

---

Widener University

We take your education personally.

Master's Program in Chemical Engineering
(Including Environmental Engineering Option)

Advanced study in chemical engineering including process analysis, synthesis and design.

Core Courses . . . Thermodynamics • Transport phenomena • Reaction kinetics • Applied mathematics

Wide range of technical electives • Thesis option

Environmental engineering option provides the know-how to apply advanced chemical engineering techniques to problems in that area.

Topics include . . .
Environmental law • Advanced water and wastewater systems • Incineration/hazardous waste management
Related program in Engineering Management and dual ME/MBA also available.

For more information contact:
Professor D.H.T. Chen • Assistant Dean/Graduate Programs and Research • School of Engineering • Widener University
One University Place • Chester, PA 19013-5792 • Phone 610/499-4198 • FAX 610/499-4059
Bucknell
Department of Chemical Engineering
MS PROGRAM

W. E. KING, Chair (PhD, University of Pennsylvania)
Laser-tissue interactions; oxygen transport in tumors

J. CSERNICA (PhD, Massachusetts Institute of Technology)
Gas and liquid transport in polymers; plastics recycling; modification of solid state polymer properties

M. E. HANYAK (PhD, University of Pennsylvania)
Applied instructional design; multimedia courseware development; chemical process analysis

J.E. MANEVAL (PhD, University of California, Davis)
NMR and NMR imaging; chromatographic and membrane separations

S. ODU (PhD, Imperial College, University of London)
Oil-water separation processes; advanced chemical/petrochemical waste treatment processes; multiphase flowing systems

J. M. POMMERSHEIM (PhD, University of Pittsburgh)
Transport phenomena (in cementitious systems); modeling of phase change systems; corrosion processes; catalyst deactivation

M. J. PRINCE (PhD, University of California, Berkeley)
Hydrodynamics and transport phenomena in biochemical systems; environmental barrier design

W. J. SNYDER (PhD, Pennsylvania State University)
Polymer degradation; kinetics; catalysis; specific ion electrodes; drag reduction; solution thermodynamics

Bucknell is a small, private, highly selective university with strong programs in engineering, business, and the liberal arts. The Department is located in the Charles A. Dana Engineering Building which provides state-of-the-art facilities for both computational and experimental research. Graduate students have a unique opportunity to work very closely with a faculty research advisor.

Lewisburg, located in the center of Pennsylvania, provides the attraction of a rural setting while conveniently located within 200 miles of New York, Philadelphia, Washington, D.C., and Pittsburgh.

For further information, write or phone
Dr. William E. King, Chair • Chemical Engineering Department
Bucknell University • Lewisburg, PA 17837
Phone: 717-524-1114
or visit our website at http://www.bucknell.edu/

Brown University
Graduate Study in Chemical Engineering

Research Topics

Chemical kinetics • combustion • fluidized beds • separation processes • environmental problems • numerical simulation • vortex methods • turbulence • hydrodynamic stability • coal chemistry • coal gasification • heat and mass transfer • aerosol condensation • transport processes • membranes • particulate deposition • physiological fluid mechanics • rheology

A program of graduate study in Chemical Engineering leads toward the M.Sc. or Ph.D. degree.

Teaching and Research Assistantships as well as Industrial and University Fellowships are available.

For further information, write:
Professor J.M. Calo, Coordinator
Chemical Engineering Program
Division of Engineering
Brown University
Providence, Rhode Island 02912

LOWELL
University of
Massachusetts
College of Engineering
Department of Chemical and Nuclear Engineering

We offer professionally oriented engineering education at the M.S., Ph.D., and D.E. levels

In addition we offer specialization in

• BIOPROCESS ENGINEERING •
• BIOTECHNOLOGY •
• COMPUTER-AIDED PROCESS CONTROL •
• ENERGY ENGINEERING •
• ENGINEERED MATERIALS •
• PAPER ENGINEERING •
• POLYMERIC MATERIALS •

Please call (978) 934-3171 or write for specifics to

Dr. T. Vasilos (Chemical Engineering)
Dr. J. R. White (Energy Engineering)
Graduate Coordinators
One University Avenue
Lowell, MA 01854

Fall 1997
South Dakota School of Mines and Technology

M.S. in Chemical Engineering
M.S. in Materials Engineering Science

We offer the M.S. degree in Chemical Engineering with small classes, opportunities for teaching or research assistantships after the first semester, and thesis or non-thesis options. For individuals wishing to pursue a degree off campus, we offer distance learning courses utilizing video tapes, one-on-one contact with instructors through Internet, video phones, and other communication technologies.

We also offer the M.S. degree in Materials Engineering and Science with an emphasis in chemistry. Both thesis and non-thesis options are available for on-campus study in this program.

Both programs can lead to admission to our Ph.D. degree in Materials Engineering and Science program.

For more information and to review our current research areas, visit our WWW page at http://www.sdsmt.edu/campus/chem/chem.html

For information contact
Dr. Robb M. Winter, Graduate Admissions
Chemistry and Chemical Engineering Department
South Dakota School of Mines and Technology
501 East Saint Joseph Street
Rapid City, South Dakota 57701
Phone: (605) 394-1237 • Fax (605) 394-1232 • rwinter@silver.sdsmt.edu

MONTANA STATE UNIVERSITY

Research Emphases
Materials Science
Composite Materials
Development & Testing
(including the new wind turbine testing facilities)
Surface Chemistry
Biotechnology
Biofilm & Bioremediation
with the NSF Center for Biofilm Engineering
Separations
Distillation & Membranes

UNIVERSITY OF NORTH DAKOTA

MS and MEngr. in Chemical Engineering Graduate Studies

PROGRAMS: Thesis and non-thesis options available for MS degree; substantial design component required for M.Engr. 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. A PhD program in Energy Engineering is also available to students with MS in Chemical Engineering.

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 AND ENVIRONMENTAL 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 a limited number of students.

FOR INFORMATION WRITE TO
Director of Graduate Admission
Chemical Engineering Department
University of North Dakota, Box 7101
Grand Forks, North Dakota 58202
(701-777-4244)

Chemical Engineering Education
### ACKNOWLEDGEMENT

**DEPARTMENTAL SPONSORS**

The following 162 departments contribute to the support of CEE with bulk subscriptions.

*If your department is not a contributor, write to CHEMICAL ENGINEERING EDUCATION c/o Chemical Engineering Department • University of Florida • Gainesville, FL 32611-6005 for information on bulk subscriptions*

<table>
<thead>
<tr>
<th>Department Name</th>
<th>State</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Akron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Alabama</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Arizona</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arizona State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Arkansas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auburn University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ben Gurion University of the Negev</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brigham Young University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of British Columbia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bucknell University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of California, Berkeley</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of California, Davis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of California, Irvine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of California, Los Angeles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of California, San Diego</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of California, Santa Barbara</td>
<td></td>
<td></td>
</tr>
<tr>
<td>California Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>California State Polytechnic Institute</td>
<td></td>
<td></td>
</tr>
<tr>
<td>California State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carnegie-Mellon University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case Western Reserve University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Cincinnati</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarkson University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clemson University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Colorado</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colorado School of Mines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colorado State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Columbia University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Connecticut</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cork Regional Technical College</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cornell University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dartmouth College</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Dayton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Delaware</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drexel University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Edinburgh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Florida</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florida Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florida State/Florida A&amp;M University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Georgia Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hampton University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Houston</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Howard University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Idaho</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Illinois, Chicago</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Illinois, Urbana</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illinois Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Iowa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iowa State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Johns Hopkins University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Kansas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kansas State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Kentucky</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lafayette College</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lakehead University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lamar University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laval University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lehigh University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loughborough University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Louisiana State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Louisiana Technical University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Louisville</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Maine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manhattan College</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Maryland</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Maryland, Baltimore County</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Massachusetts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Massachusetts, Lowell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McGill University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McMaster University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McNeese State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Michigan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michigan State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michigan Technical University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Minnesota</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Minnesota, Duluth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Mississippi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mississippi State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Missouri, Columbia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Missouri, Rolla</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montana State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Nebraska</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Nevada at Reno</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of New Hampshire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of New Haven</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Jersey Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of New Mexico</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Mexico State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Carolina A &amp; T University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Carolina State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of North Dakota</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northeastern University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northwestern University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Notre Dame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical University of Nova Scotia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ohio State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ohio University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Oklahoma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oklahoma State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oregon State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Ottawa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Pennsylvania</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pennsylvania State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Pittsburgh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polytechnic Institute of New York</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Princeton University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purdue University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Queen's University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rensselaer Polytechnic Institute</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Rhode Island</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Rochester</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rose-Hulman Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rowan College</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rutgers, The State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ryerson Polytechnic University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Jose State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Saskatchewan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Sherbrooke</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of South Alabama</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of South Carolina</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Dakota School of Mines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of South Florida</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Southern California</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Southern California</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Southwestern Louisiana</td>
<td></td>
<td></td>
</tr>
<tr>
<td>State University of New York, Buffalo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stevens Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Sydney</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syracuse University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Tennessee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tennessee Technological University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Texas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texas A &amp; M University, College Station</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texas Tech University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Toledo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tri-State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tufts University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Tulsa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Utah</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vanderbilt University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Villanova University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Virginia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Virginia Polytechnic Institute</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Wales, Swansea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Washington</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washington State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washington University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Waterloo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wayne State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Virginia Graduate College</td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Virginia Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Virginia University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Widener University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Wisconsin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worcester Polytechnic Institute</td>
<td></td>
<td></td>
</tr>
<tr>
<td>University of Wyoming</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yale University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Youngstown State University</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>