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# chemical engineering education

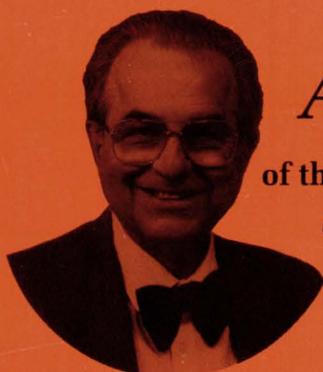


VOLUME XXV

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Summer 1991

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION



## ANDREAS ACRIVOS

of the

City College, City University of New York

*A Simple Heat of Crystallization Experiment*  
DE NEVERS

*Development and Use of Open-Ended Problems*  
AMYOTTE

*Errors: A Rich Source of Problems and Examples*  
WHITING

*Introduction to Equilibrium Thermodynamics: Part 2*  
WILLIAMS • GLASSER

*Inventing Multiloop Control Systems with Interactive Graphics*  
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*Novel Freshman Class to Introduce ChE Concepts and Opportunities*  
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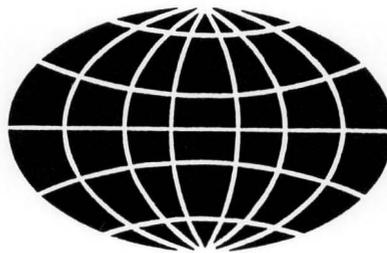
*Determining the Kinetic Parameters Characteristic of Microalgal Growth*  
MARTINEZ • BRAVO • SÁNCHEZ • MOLINA

*Chemical Reaction Engineering Applications in Non-Traditional Technologies*  
SAVAGE • BLAINE

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# ANDREAS ACRIVOS

*of The City College, City University of New York*

SHELDON WEINBAUM, L. GARY LEAL<sup>1</sup>  
*City College of CUNY*  
*New York, NY 10031*

When Benjamin Levich passed away, New York State's only Albert Einstein Chair in Applied Science and Technology became vacant. All of the State institutions compete vigorously for this prestigious chair, so there was little hope for keeping it at City College unless a candidate of truly unusual reputation and achievements could be located. That person was found behind an ever-present black bow tie: Andreas (Andy) Acrivos, a *mentor of mentors*.

In addition to holding the Albert Einstein Chair in Applied Science and Technology at City College, Andy is editor of *The Physics of Fluids*, a past chair of the U.S. National Committee on Theoretical and Applied Mechanics, director of the Levich Institute at City College, and a member of the NAE and of the NAS. Beyond these more visible activities, he has also played a major leadership role in establishing fluid mechanics within the AIChE, has helped broaden the purview of the Fluid Dynamics Division of the APS, and has ably represented the field in the larger scientific community. As a result of his wide-ranging research interests he holds joint appointments in three departments at City College—chemical engineering, mechanical engineering, and physics.

Two of us have undertaken to write this article since we know Andy from different perspectives—one as a former student from the early days when he first came to Stanford University, now a colleague, and the other as a recent collaborator and colleague who was instrumental in spirited him away from Stanford. We shall each try to impart some of our personal perceptions.

## THE VIEW BEHIND THE SCENES

Many have questioned how Andy could leave the comfortable and affluent surroundings of a prestigious private university such as Stanford to start

<sup>1</sup> University of California, Santa Barbara, CA 93106



*Andy and Jennie with his former advisor,  
 Neal Amundson*

his academic life anew at a school known for economically-deprived, hard-working immigrants and minorities—a school with few frills and where everyone is a commuter. In fact, one supporting letter for the Einstein Chair stated, "If you succeed in wooing Andy to City College, 'mazel tov,'— we have been trying for ten years without success."

The answer is that we realized that Andy was a hard-working immigrant himself (born in Greece in 1928; BS, Syracuse University, 1950; PhD, University of Minnesota, 1954; mentor, Neal Amundson) and that he would probably love the melting-pot excitement, culture, and restaurants that make up New York; that he would not be intimidated by its subways and the backways of Harlem. Even more important, we felt that he would be intrigued by the challenge of developing an Institute for Physico-Chemical Hydrodynamics at an institution where past students include eight Nobel Laureates and which is often referred to by its alumni as the "Harvard of the Proletariat." When one prominent alumnus returned recently to give a seminar, he opened his talk with the remark, "I remember fondly when I would take the subway up to Harlem from Brooklyn and then walk up Convent Avenue, but I guess that is part of the past." Acrivos quickly retorted, "I do

**TABLE 1**  
**Acrivos' PhD Students Now In Teaching**

PhD in	Name	Current Affiliation, Rank
1959	D. Wilde	Stanford University, <i>Professor, Mechanical Engineering (retired)</i>
1960	E. Gose	University of Illinois, Chicago Circle Campus, <i>Professor</i>
1961	J.D. Goddard	University of California, San Diego <i>Professor, Chemical Engineering</i>
1963	F.H. Shair	California State University, Long Beach, <i>Dean of Natural Sciences</i>
1964	J.C. Berg	University of Washington, <i>Professor, Chemical Engineering</i>
1967	R.E. Davis	Scripps Institute, U.C. San Diego, <i>Professor, Oceanography</i>
1969	L.G. Leal	Univ. of California, Santa Barbara, <i>Professor, Chemical Engineering</i>
1970	C.R. Robertson	Stanford University, <i>Professor, Chemical Engineering</i>
1972	D. Barthes-Biesel	University of Compiègne (France), <i>Professor</i>
1973	W.B. Russel	Princeton University, <i>Professor, Chemical Engineering</i>
1973	A. Nir	Technion, Israel, <i>Professor, Chemical Engineering</i>
1973	C.A. Kossack	University of Trondheim (Norway), <i>Professor, Petroleum Engineering</i>
1979	F. Gadala-Maria	University of South Carolina, <i>Associate Prof., Chemical Engineering</i>
1982	R.H. Davis	University of Colorado, <i>Associate Professor, Chemical Engineering</i>
1982	A. Sangani	Syracuse University, <i>Associate Professor, Chemical Engineering</i>
1985	D.T. Leighton	University of Notre Dame, <i>Assistant Professor, Chemical Engineering</i>
1987	E.S.G. Shaqfeh	Stanford University, <i>Assistant Professor, Chemical Engineering</i>
1988	A. Borhan	Pennsylvania State University, <i>Assistant Prof., Chemical Engineering</i>

**TABLE 2**  
**Acrivos' Students: Presidential Young Investigators**

J.F. Brady
R.H. Davis
D.T. Leighton
E.S.G. Shaqfeh
G.G. Fuller ( <i>Leal's former student</i> )
A.P. Gast ( <i>Russel's former student</i> )
S. Kim ( <i>Russel's former student</i> )
P. Frattini ( <i>Fuller's former student</i> )
S. Karel ( <i>Robertson's former student</i> )
H.A. Stone ( <i>Leal's former student</i> )
D.L. Koch ( <i>Brady's former student</i> )
N.J. Wagner ( <i>Russel's former student</i> )
J.J.L. Higdon ( <i>former post-doc</i> )

that every day, and sometimes at 10 o'clock at night!"

A major concern in recruiting Acrivos was Jennie, who (after thirty-five years of marriage) Andy still affectionately refers to as his bride. Jennie, also an immigrant (from Cuba), is a prominent physical chemist with a distinguished career of her own. She is a regular visitor to the Cavendish Laboratory at Cambridge University (where she has collaborated for many years with Sir Nevil Mott), in addition to being a former Fellow of Trinity College in Cambridge and a recent recipient of an NSF Visiting Women's Professorship. She is a professor at California State University, San Jose, but often divides her time between that campus and Berkeley since her campus does not have doctoral students.

Although Andy and Jennie both have demanding careers, have often had to travel separately, and have had visiting academic appointments in separate places, living between two homes on opposite coasts would be quite different, and there was some initial trepidation over the possibility of living apart. However, the Acrivos' philosophy is to try to maintain travel between the best of two worlds and when working, work hard, . . . when playing, play hard, . . . and in between talk on the phone every night.

It is not so surprising that Andy would be willing to interrupt a successful career and accept the challenge and risk of building a new institute at a new location. Early in his professional life, Andy abandoned the established grounds of chemical engineering at Berkeley and accepted an invitation (from Dave Mason, then chair) to join a program at Stanford that was just getting off the ground and attempting to establish itself as a teaching and research force in the field. Together he, Michael Boudart (also recently arrived from Berkeley), and his new colleagues quickly catalyzed Stanford's rapid rise to one of the top departments in the country.

## ANDY—THE TEACHER

While Andy has been a mentor to more than forty PhD students, even more extraordinary is the fact that nearly half of them now hold academic appointments of their own (see Table 1). Many of his students, influenced by his high expectations and standards, are now recognized for their own achievements. Three of them (A.S. Grove, L.G. Leal, and R.E. Davis) are members of the NAE or NAS, and twelve of his former students, or their students, and one post-doc have been recipients of Presidential Young Investigator Awards (see Table 2).

Andy's broad outlook has also rubbed off on many of his students, and several have developed reputations quite outside the subject matter of their dissertations, e.g., A.S. Grove (semiconductors), R.E. Davis (oceanography), W.B. Russel (colloids), J.B. Klemp (atmospheric science), and C.R. Robertson (bioengineering).

Andy's impact as a mentor to his research students has already been mentioned. However, his influence on academic life at Stanford was far more pervasive than any list of forty PhD students can indicate. A student's first experience as a new PhD at Stanford (independent of research and career goals and the like) was to appear at 8 A.M. on the first day of class (and three times a week thereafter) to participate in Andy's graduate transport course. The subject matter was mostly asymptotic analysis of transport problems, largely based on Andy's own original research papers, but the "gift" carried away by all students (and enduring long after their asymptotic skills may have become rusty) was the ability to think clearly, logically, and innovatively. Of course, this gift was likely to become evident later rather than sooner in a student's career, so the ma-

**TABLE 3**  
**Acrivos' Most Frequently Cited Papers**

1. "On the Steady State Fractionation of Multicomponent and Complex Mixtures in an Ideal Cascade: Part 1, Analytic Solution of the Equations for General Mixtures,"  
A. Acrivos, N.R. Amundson; *Chem. Eng. Sci.*, **4**, 29 (1955)
2. "Heat and Mass Transfer From Single Spheres in Stokes Flows,"  
A. Acrivos, T.D. Taylor; *Phys. Fluids*, **5**, 387 (1962)
3. "An Experimental Investigation of the Steady Separated Flow Past a Circular Cylinder,"  
A.S. Grove, F. H. Shair, E.E. Petersen, A. Acrivos; *J. Fluid Mech.*, **19**, 60 (1964)
4. "Steady Flows in Rectangular Cavities,"  
F. Pan, A. Acrivos; *J. Fluid Mech.*, **28**, 643 (1967)
5. "Solitary Internal Waves in Deep Water,"  
R.E. Davis, A. Acrivos; *J. Fluid Mech.*, **29**, 593 (1967)
6. "Stokes Flow Past a Particle of Arbitrary Shape: A Numerical Method of Solution,"  
G.K. Youngren, A. Acrivos; *J. Fluid Mech.*, **69**, 377 (1975)
7. "Deformation and Burst of a Liquid Droplet Freely Suspended in a Linear Shear Field,"  
D. Barthes-Biesel, A. Acrivos; *J. Fluid Mech.*, **61**, 1 (1973)
8. "Enhanced Sedimentation in Settling Tanks with Inclined Walls,"  
E. Herbolzheimer, A. Acrivos; *J. Fluid Mech.*, **92**, 435 (1979)
9. "Shear-Induced Structure in a Concentrated Suspension of Solid Spheres,"  
F. Gadala-Maria, A. Acrivos; *J. of Rheology*, **24**, 789 (1980)
10. "The Shear-Induced Migration of Particles in Concentrated Suspensions,"  
D. Leighton, A. Acrivos; *J. Fluid Mech.*, **181**, 415 (1987)

**Recognition for his scientific achievements came very early. His first academic appointment at Berkeley was only eight years long...but by the time he arrived at Stanford...he had published his fortieth paper...**

jour challenge of the moment was to get to Andy's class before 8 A.M.—it was impossible to slip unnoticed into class at 8:01 A.M.!

Andy has always given one-hundred percent of himself to his academic endeavors, and he demanded no less of anyone expecting to receive a PhD from Stanford. His friendly interest and penetrating inquiries extended to all students and all facets of their research. Most chemical engineering departments find that seminar attendance is a problem, but during Andy's years at Stanford this was not the case. Prior to introductions, he would stand up in front of the room and make a rapid visual survey of attendees. Non-attendance by anyone, graduate student or faculty member alike, would be noted and commented upon at their next meeting.

All departments exhibit their own personality, and in the early days it took only a casual glance to see Andy's imprint on the Stanford department. His legacies of quality, absolute integrity, and a lifelong ability to get somewhere before 8 A.M. are shared by all those who were fortunate enough to be students under Andy's influence.

## ANDY—THE RESEARCHER

Andy has been the author or coauthor of over 160 full-length journal articles during his thirty-seven years in academia. He has been one of the most prolific contributors to the *Journal of Fluid Mechanics* (45 papers to date), and many of his papers are viewed as cardinal contributions that initiated new ideas or approaches to solving problems which have been widely adopted by later investigators.

Recognition for his scientific achievements came very early. His first academic appointment at Berkeley was only eight years long (1954-62) but by the time he arrived at Stanford in 1962 he had already published his fortieth paper and was shortly to receive the A.P. Colburn Award of the AIChE. A selection of ten of Andy's most frequently cited papers is given in Table 3.

Andy is widely recognized for his major contributions to the modern theory of fluid, heat, and mass transport processes. In his earliest work (begun as a PhD student with Neal Amundson) he became well-

known for his elegant use of advanced mathematical techniques to analyze the dynamics of separation processes. Later, beginning about 1960, Andy and his students became involved with the development and application of asymptotic analysis to a wide variety of problems in fluid mechanics, especially those in heat and mass transfer. This work revolutionized existing understanding of scaling laws and correlations between dependent and independent dimensionless parameters in transport systems.

Then came work on internal wave propagation, the response of heated fluids to Marangoni and buoyancy driven instabilities, and a long (still continuing) quest to understand the asymptotic nature of flows in the limit of high Reynolds numbers. In more recent years, Andy has done very important work on suspension mechanics, enhanced gravitational sedimentation, transport processes in suspensions, and low Reynolds number hydrodynamics, including an extensive series of studies on drop deformation and breakup (which involves the development of new numerical techniques for treating the non-linear coupling between the droplet shape and the surrounding flow field). A new effort is the phase separation of red and white blood cells at microvascular bifurcations and particle entrainment at small side pores.

The hallmarks of Andy's collected body of research are its breadth, the quality of virtually every paper to which he has been a contributor, and the impact that his work has had on other researchers. Andy had blazed many new trails in breaking artificial barriers which had previously limited the scope and range of problems and techniques within fluid mechanics. The resulting legacy from Andy, and others like him, can be clearly seen today in the cross-disciplinary identities of the authors of research papers in the leading fluid mechanics journals.

#### ANDY—THE FAMILY MAN AND FRIEND

The examples set by Andy and Jennie, individually and as partners, were lofty and worthy standards for emulation, but in certain areas the goals were impossible to attain. One area was Andy's mastery of games. In 1947 he placed second in the U.S. Intercollegiate Chess Championship, losing to U.S. Grand Master Robert Byrne (currently the *New York Times* chess editor). A virtual unknown in chess circles at the time, Andy's picture was chosen for the cover of *Chess Review* and pictures of that championship game with Byrne still adorn the wall above his desk. Less obvious was his prowess at bridge, a

game which he claimed not to play but which the noon-time addicts often persuaded him to join, much to their chagrin when he would casually pull off a grand slam.

Andy has always been interested in current problems of the day, whether they fit into a pre-established mold of what he already knows or what his colleagues deem appropriate for chemical engineers. This gives his students a chance to play a part on the "world stage" of fluid mechanics, including the opportunity to test their abilities in making a contribution, even among such exalted company, and thus to



*Andy's 60th birthday party with his former advisor and some of his former students.*

develop the self-confidence required for a successful research career.

Many of his former students continue to visit him at the Institute, where there is a feeling of family even though there is still no nonsense when it comes to science. No one is spared from his probing inquiries or his sometimes disbelieving questions at a seminar. As a collaborator, there is an unwritten understanding that nothing will be published until it is "poifect," even if the galleys have arrived.

It is no accident that Andy has had so many academic offsprings and collaborators since he holds a continuing interest in his students and their activities long after their departure. That interest and concern is mutual. Recently, many of his former students, dispersed around the globe, traveled great distances to be present at his student-organized 60th birthday celebration.

As a research advisor, Andy commanded (but never demanded) respect. He was addressed as "Professor Acrivos" right up to the day a student earned his PhD, but was magically "Andy" forever after that day. □



*View of the south end of the campus across a campus pond.*

**ChE** department

## **UNIVERSITY OF MASSACHUSETTS**

**C**hemical engineering at the University of Massachusetts is a vigorous program with a distinctive vision. Traditional strengths are built on within reaction engineering and separations. At the same time, we address contemporary opportunities in areas of polymeric and electronic materials. Meanwhile, we are blending new approaches to macro-scale design and molecular-scale chemistry with the power of transport phenomena, creating a new perspective on chemical engineering.

The University is situated in a picturesque section of New England along the Connecticut River valley. Ninety miles to the east is Boston and the coast, the Berkshires lie to the west, and New York City is about a four-hour drive to the south. Although Amherst is a small town with a population of about 25,000 residents, it has been home to a surprisingly large number of prominent citizens, including poets Emily Dickinson and Robert Frost, lexicographer Noah Webster, and sculptor Daniel Chester French.

In this scenically and intellectually rich environment, our department has grown in a relatively brief time. Between 1951 and 1966, it evolved from a small undergraduate department to a modest-sized program offering undergraduate and graduate degrees to the MS level. The first PhD degree was awarded in 1968. Since then, the program has ma-

tured into an established teaching and research department granting about thirty BS, five MS, and thirteen PhD degrees each year.

The chemical engineering department was begun within the fledgling School of Engineering in 1951 by Ernie Lindsey, formerly of Yale. It was a small program during its first ten years, with five faculty, twenty seniors each year, and no graduate program.

In 1962, John Eldridge accepted the task of forging a graduate program in chemical engineering during a time of incredible growth and change in Amherst. In the ten years between 1960 and 1970, UMass grew from 8,000 to over 20,000 students. It was a vital time when everyone was eagerly building programs, and John's persistence, optimism, and charm worked wonders for the department. In eight years he hired eleven new faculty, saw a miniscule graduate program grow to fifty-five students, and found new research funds and space.

In 1976, after fourteen years of building a program, Eldridge let the reins fall to Leigh Short. These were difficult economic times for New England, however, and Leigh left the university in 1978, leaving Jim Douglas to serve as interim head for a year while the search for a new head got under way. Jim used the opportunity to begin planning activities that brought new focus and new directions to

the program. As a result he was appointed head of the department and remained until 1982 when Bob Laurence took over. The ten years during which Douglas and Laurence had responsibility was another period of dramatic growth. It was a period when research activity grew significantly and new faculty were taken on board. When Bob decided to step down, Mike Doherty became head.

Twenty-three years have passed since the first PhD was awarded. Since then, 132 PhDs have completed their work in chemical engineering and an additional 37 PhDs from the Polymer Science and Engineering Department have been advised and supported by chemical engineering faculty.

In 1966 the chemical engineering and chemistry departments played a key role in the creation of a new program—Polymer Science and Engineering (PSE), a program of international prominence. The two departments have close ties, and over the years there have been many chemical engineering students advised by PSE faculty and vice versa.

## PHILOSOPHY OF THE DEPARTMENT

The large turnover of faculty during the years from 1977 to 1986 gave us an opportunity to restruc-

ture the department, and after numerous discussions we decided to try some different approaches. Although the general departmental model at that time was for each faculty member to be an expert in a single area, we decided to build groups of three to five faculty, each with a different viewpoint, who would work in the same general area. We hoped that the "creative tensions" encountered in each group would lead to novel approaches. In addition, our goal was to get members of the specific areas to engage in dialogue with members of other groups and in this way to define significant research problems at the interfaces between traditional problem areas.

All of us love to learn and love to teach. Hence, we made a commitment to integrate our research programs as much as possible with both our undergraduate and graduate curricula. That is, we would transfer research results to our undergraduate and graduate courses as quickly as possible. We would periodically revise the undergraduate and graduate courses, and when we had developed enough new material we would write new textbooks based on our ideas. The first two books to be written out of this period were Jim Douglas' book, *Conceptual Design of Chemical Processes*, and Julio Ottino's book, *The Kinematics of Mixing: Stretching, Chaos and Transport*. Readers familiar with these books will probably agree that they represent rather significant departures from traditional thinking. Other books are also currently under way.

We also decided to try to achieve a better balance between fundamental science and process engineering. Thus, we hoped to develop different approaches for solving widely recognized practical problems of importance, such as process design, polymer engineering, solids processing, and mixing problems. This effort would be balanced by programs focused on fundamentals such as kinetics and catalysis, thermodynamics, fluid mechanics, etc. Most of the design research at that time was focused on the computational



Department heads in action: John Eldridge and fishy friend (left); Jim Douglas in full highland dress (above); and Bob Laurence (below) who is also the varsity rugby coach.



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*As a statement of commitment to our teaching and scholarship, the faculty agreed to rotate the teaching of our undergraduate courses every three or four years.*

---

problems associated with flowsheeting and optimization. We decided to focus instead on process synthesis and conceptual design. We expected that a new approach to conceptual design would provide better material to teach undergraduates than the design courses that were taught to most of us.

Traditionally we had strong interaction with the Polymer Science and Engineering Department, and several faculty had joint appointments in both departments. We had a strong support base in polymer chemistry and one of the large and rapidly growing areas of material science. We could use this support base to develop a stronger research program in polymer processing operations and the design of flowsheets for complete polymer plants. In conjunction with the Polymer Science and Engineering Department we have developed several joint courses at both the undergraduate and graduate levels. In addition, we have incorporated polymer components in many of the traditional chemical engineering courses, including the undergraduate laboratory which has an extruder, a blow molder, and a methyl methacrylate polymerization experiment.

When we considered the scales of chemical technology, which cover the spectrum of scales from molecular to continuum to unit operations and finally complete plants, it was clear that we had several faculty with strong backgrounds in transport phenomena and unit operations. Therefore, we decided to bring in faculty who would strengthen our chemistry expertise in the areas of catalysis, design of unconventional reactors (ceramic membranes and magnetically stabilized fluid beds), statistical thermodynamics and adsorption, molecular kinetics and applications in emerging areas of technology, and quantum mechanics and applications to materials.

For many years there have been growing complaints that chemical engineering students do not know enough chemistry. Even a cursory examination of the curriculum at that time indicated that the focus was limited to physics and mathematics and that we had essentially purged chemistry from the engineering courses. One of our goals became to look for ways to include some chemistry, as well as a molecular perspective, in many of the undergraduate courses.

Our research results have led to a complete re-

structuring of the graduate and undergraduate design courses, as well as our separations course (much of this course is now focused on the separation of multicomponent nonideal mixtures). Currently, Jim Douglas is moving much of the synthesis material down into the introductory course. The new course is a major revision of the old industrial chemistry courses. Instead of memorizing flowsheets, students are given a set of reactions that produces a product and are taught how to invent a flowsheet. The invention of a flowsheet provides a context for studying phase diagrams, vapor-liquid equilibria, and other introductory material normally covered in the first chemical engineering course. Then the students develop the material and energy balances for the flowsheets, as well as the raw material costs and the utilities costs. This approach has the advantage of solving open-ended problems from the outset, and it provides a context for the remainder of the curriculum. At the same time, Phil Westmoreland is creating a senior/graduate-level course on the "Chemistry of Chemical Engineering." His focus is teaching the use of modern techniques to estimate and correlate thermochemistry, kinetics, and physical properties based on molecular structures. Curt Conner has also developed a senior/graduate-level elective course, "Advanced Engineering Solids," which integrates structure, properties, and manufacturing processes for a variety of "high-technology" solids.

As a statement of commitment to our teaching and scholarship, the faculty agreed to rotate the teaching of our undergraduate courses every three or four years. This policy has been in existence for about a decade, and most of our faculty are now capable of teaching many of the courses in the curriculum, including the undergraduate lab! One of the great advantages of this policy is that it substantially widens the expertise of the faculty.

There are five major thrusts in the department: process design and control, polymer engineering, kinetics and catalysis, transport processes, and applied theoretical chemistry. Each thrust has several faculty and graduate student participants and many faculty have their feet in more than one camp. A brief discussion of these thrusts follows.

### ***Design and Control***

There is a major research effort in the areas of process design and control involving Mike Doherty, Jim Douglas, Mike Malone, Ka Ng, and Erik Ydstie. The programs have close ties with industry, including an Industry/University Center which was established in 1985. Regular meetings on campus provide students with an opportunity to meet industrial sponsors and give updates on recent research

results. The Center receives no direct government support, but contributions from the sponsors supplement and complement substantial government and industrial research funding of the individual faculty in the general area of chemical process design and control.

Research results also provide important feedback for the evolution of the graduate and undergraduate curriculum. New materials are often taught first in short courses to practicing engineers; more than thirty short courses in conceptual design and six in distillation systems have been taught in the last ten years. Some of the material is then incorporated in course offerings at the university, throughout the undergraduate program, and in the graduate process design and control courses.

### **Polymer Engineering**

The department has a long tradition of research and teaching in polymer engineering that began in the 1960s with Bob Lenz, Bob Laurence, and Stan Middleman, who between them covered much territory from polymer synthesis, kinetics, and characterization to polymer diffusion, reactor engineering, rheology, and polymer processing. The effort was expanded significantly around 1980 with the addition of Julio Ottino, Mike Malone, and Henning Winter. They all came with backgrounds in fluid mechanics (albeit with very different perspectives), and each developed his own unique niche in the polymer business.

Today we find a wide spectrum of interests in this field. Molecular-scale phenomena such as molecular orientation are studied in order to understand the behavior of liquid-crystal polymers and the properties of blends. A variety of experiments has been designed to probe these systems, including fluorescence and light-scattering techniques. Polymer processing is studied to find the influence of the elasticity of the material on the processability and on the molecular orientation in the flow.

Several projects explore the relationship between transport and morphology in polymer blends, mixed polymer systems, and copolymers. Research in this area involves theory, experiments, and novel computer image analysis.

In recent years a novel effort has been initiated to explore the design and optimization of batch and continuous processes for polymer production. A systems approach shows interactions of process components, economic trade-offs, and optimal flowsheet design. For teaching purposes, this approach has the attraction of identifying design problems where non-trivial transport effects (velocity gradients, diffusion, *etc.*) play dominant roles in the design calculations. For such processes, our old and friendly assumptions like "well mixed" and "plug flow" rarely give satisfactory results, especially in the finishing operations of polymer processing.

### **Reaction Systems**

Another large research effort is directed toward a wide variety of problems involving chemical reactions. Seven faculty direct approximately twenty graduate students in problems spanning heterogeneous metal and metal oxide catalysis, chemical vapor deposition, reaction and separa-

tion by reactive distillation or with catalytic inorganic membranes, and multiphase catalysis.

There is a strong element of chemistry in these projects. Phil Westmoreland and his students measure detailed compositions of steam-cracking products and of free radicals and stable species within flames; then they interpret the reaction chemistry with reactor models involving

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***There are five major thrusts in the department: process design and control, polymer engineering, kinetics and catalysis, transport processes, and applied theoretical chemistry...many faculty have their feet in more than one camp.***

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200 to 1000 elementary reactions. The observation of phenomena such as steady-state multiplicity and oscillations and measurement of more conventional kinetic trends provide the basis for Mike Harold's procedure of kinetic model development and discrimination for a wide class of noble-metal-catalyzed oxidation reactions. Together with Curt Conner, Harold uses Fourier-transform infrared spectroscopy to monitor surface species and catalyst structure during reaction on metal oxide catalysts. Val Haensel studies molecular rearrangement, fragmentation, and scavenging in metal-catalyzed hydrocarbon reactions.

Interactions between reaction and transport processes are of paramount importance for chemical reactor analysis and design. The common approach used in several of these projects is the focus at the local level. Conner and Laurence observe and model reaction and transport during olefin polymerization in a fragmenting catalyst pellet. Harold and Ng are concerned with multiphase transport-reaction interactions and their impact on performance of multiphase reactors. Progress towards the development of a realistic trickle-bed reactor model exploits Ng's focus on local flow features and Harold's focus on single-pore and pellet multiphase reaction and diffusion phenomena.

In addition to the polymerization and multiphase reactor projects, several new types of reactors are being developed for use in emerging technologies. Doherty studies simultaneous reaction and distillation of components in highly nonideal liquid mixtures. Design and synthesis schemes are being developed to achieve reaction and separation in a single unit. Coupled reaction and separation is also a motivation for Harold's development of catalytic ceramic membranes. A new type of catalytic membrane reactor has been developed which segregates the gas and liquid streams and thus reduces mass transport limitations for the wide class of volatile-reactant-limited multiphase reactions. Westmoreland's understanding of plasma chemistry provides the basis for improved plasma-enhanced CVD reactors.

### **Transport Processes**

Several research projects focus on problems of fluid dynamics, rheology, porous material characterization and mass transport. An underlying theme in these projects is

# INVENTING MULTILoop CONTROL SYSTEMS IN A JIFFY WITH INTERACTIVE GRAPHICS

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Inventing multiloop control systems isn't easy—especially multiloop systems for chemical processes. That's the usual task facing us as chemical engineers; attending to the regulation and coordination of many variables is what makes the task difficult.

For example, consider being presented with a challenge to synthesize a control system (and to demonstrate that it works!) for the little process shown in Figure 1. The distillation column in this process is to produce a top product with impurity not exceeding one percent, and it must do so during production rate changes requested by the sales force and during unexpected appearances of a reaction-rate inhibitor in the reactant feed to the CSTR. But that's not all: during such process upsets and production-rate changes, the reactor must be guarded against overflowing and the distillation column must not be allowed to flood or weep. There are eight valves and twelve measurements.

What to do?



Exploring new approaches to educating students in process control systems has been a major activity of Alan Foss in recent years. These new approaches are coming to flower now, thirty years into his teaching career at Berkeley. Prior to his Berkeley years he practiced engineering with the DuPont Company. He studied chemical engineering at Worcester Polytechnic Institute and the University of Delaware.

Peter Goodeve is a software development engineer and consultant at UC Berkeley and with other organizations. He received a BSc degree in psychology from University College London and an MS in human factors engineering from UC Berkeley. His particular computer programming expertise includes real-time control and the development of efficient user interfaces.

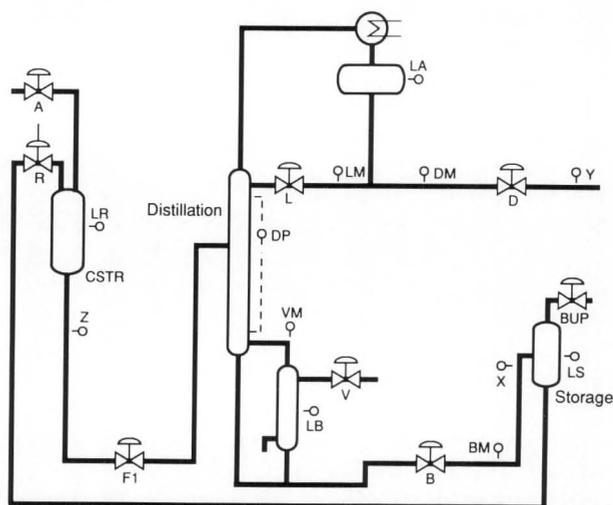
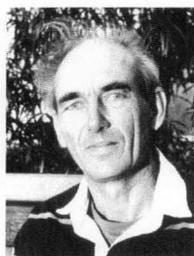


FIGURE 1. Diagram of a reaction and separation process used as a three-week project in control system synthesis and implementation. (Computer display redrawn to meet publication quality standards.)

Our undergraduate students need to encounter this sort of challenge. It serves as a superb exerciser of their inventive talents—and talents they have. It is not heresy (is it?) to assert that inventive talents ought to be exercised somewhere in the curriculum? Our observation has been that students are just "itching" for this sort of opportunity after learning something about control-system concepts.

Two of our students, for example, teamed up at the tail-end of our process control course and created the system shown in Figure 2. They reckoned that they would reduce the demands on the column control system by holding a reactor conversion reasonably constant through adjustments in the residence time. The column overhead control system employs an interesting structure that produces a D/V-ratio as the output of the top product concentration controller. This system also guarded against column

flooding or weeping by incorporation of an override system to hold column differential pressure within high and low limits. An override feature also keeps the reactor from overflowing, they say.

In their report, the students said that they also tried a couple of feedforward links, but did not incorporate them into the final system because the links did not contribute much to the system's performance. Their report showed scores of system transients displaying the performance of the controlled process in the face of production rate changes and the appearance of the reaction inhibitor.

We have presented this piece of student work simply to display the capability that is available to students with this program. We dare not attempt any deeper explanation of the workings of this team's control system.

All of the above did not just spring into the students' heads as they first sketched out their thoughts about the system. It took several trials over a period of two weeks. Trying and testing must therefore be efficient and speedy.

Time is even tighter in a 3-hour laboratory. There, students have to develop control systems in tens-of-minutes, not days. We have attempted to enhance both efficiency and speed by developing a computer program that permits a student to develop a diagram of a control system configuration on the screen of an IBM AT or a PS/2 personal computer. We call

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*In their report, the students said that they also tried a couple of feedforward links, but did not incorporate them into the final system because the links did not contribute much to the system's performance.*

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this new program UC SIGNAL. It affords a rapid means of configuring the signal paths in multiloop control systems. The control system structure output by the program can be introduced into our real-time computer control program UC ONLINE and executed either on simulated processes or on laboratory apparatus. The features of UC SIGNAL and its contribution to process control instruction is the subject of this paper.

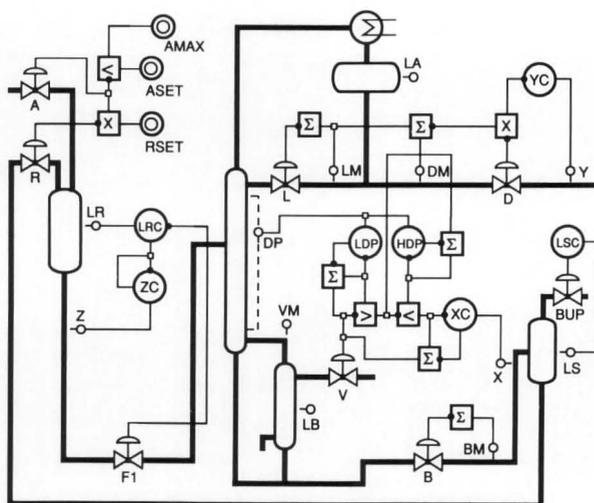
## ENHANCING THE PROCESS OF INVENTION

There are two steps in the invention process: system configuration and testing. An exercise in configuration only is not satisfactory because the student will not know whether his system is workable or how well it will perform. It is essential that there be a means to test system workability and that it be immediately available. The immediate feedback of facts about workability and performance is an essential ingredient in making the invention process speedy.

## THE CONFIGURATION STEP

We prepare a diagram of the process under consideration, such as the one in Figure 1, and display it on the computer screen. The diagram corresponds to a process simulation we have prepared or an apparatus in our laboratory. Students thus work directly with a pictorial representation of the process. The drawing of control loops is done automatically on the diagram in response to the student's declarations of the links he wants to make between measured and manipulated variables and the control elements he wants to incorporate in those links. The act of drawing the control-system structure on a diagram of the physical process (as distinguished from a conceptual abstraction) focuses the student's attention on the functionality of the control loops and the contribution they can make to the workability of the process. The visual association of the control system with the process equipment is an important and subtle element in the invention process.

Just how the student arrives at the control-system structure that he sketches is as varied as the



**FIGURE 2.** Students' control system: Configuration to regulate product quality and reactor conversion while guarding against reactor overflow and insuring that column operation is held within flooding and weeping limits. (Computer display redrawn to meet publication quality standards.)

individuals in the class. Most subject the uncontrolled simulation to step inputs through use of our program UC ONLINE, then observe the behavior of the several variables and form a cause-effect mental model. Many of them attempt (after prompting) "manual" control before settling on their first configuration. Others carry the analysis deeper by fashioning empirical quantitative representations of the responses, which are then used in a linear-system analysis and design package (*e.g.*, the program "CC" by Systems Technology, Inc.) to learn something about the underlying dynamic characteristics of the process or parts of it. The relative gain array, if it can be obtained readily, may be of some assistance when thinking about proposed configurations. Our students' decision to use a D/V-ratio in the distillation overhead system was derived from such an RGA analysis. (We have a module associated with our distillation simulation that makes the RGA analysis for the column effortless.) One can, of course, direct students to still other analytical tools if the students have been prepared for them and if computing capability is available.

## THE TESTING STEP

For control systems as complex as the one illustrated in Figure 2, the testing step is essential (at least for the student, and also for the instructor who has to be convinced of the workability of some of the labyrinthine systems). Without a demonstration of the workability of a control system and an investigation of its performance, the invention is incomplete.

This step is also essential for even the simplest control system, because inexperienced designers may not be able to think through their designs with perfect clarity. And the testing capability has to be immediately available and easily executed; otherwise reticence to use it will surely build with time as the designer gets further and further into his system development.

We feel that it is important that the system used to implement the control system be interactive, either in real time (with laboratory apparatus) or in scaled time (with process simulations). A system with such capability allows the student to observe the evolution of process variables, to debug and commission loops one by one, and to make changes in process disturbances, setpoints, tuning parameters, controller status, etc., in real time.

Students in a first course in process control should not be expected to develop a first-principles model

for a process that is as involved as the one shown in Figure 1. Most could not do it, and even if they could the exercise would not be an appropriate use of their time. A course in process control should be focused primarily on the systems problems that need to be solved in carrying out process operations. Therefore, we prepare the process model for the students. The models are then immediately available for testing a control system. They can be (and usually are) nonlinear, they can be "noisy," and they can display variations in static and dynamic character simply through changes in throughput rate. Models can be written in Fortran or C, or even fashioned by using some of the dynamic elements of our multiloop control program. Several undergraduate students have assisted us in developing these models.

The testing phase is accomplished with our interactive multiloop control program UC ONLINE.<sup>[1]</sup> We are presently using a considerably enhanced version of that program.

## LITTLE CHALLENGES AND THEIR SEQUENCING

Of course, students cannot jump into a project such as the one illustrated in Figure 1 without some preparation. We accomplish this with a sequence of laboratory projects and homework assignments of increasing sophistication over the course of the semester. All of our laboratory apparatus can be operated with any of several objectives in mind and any of a number of control system configurations.

We start very early in the semester (third week) by requiring that students use UC ONLINE to access measurements of laboratory process variables,

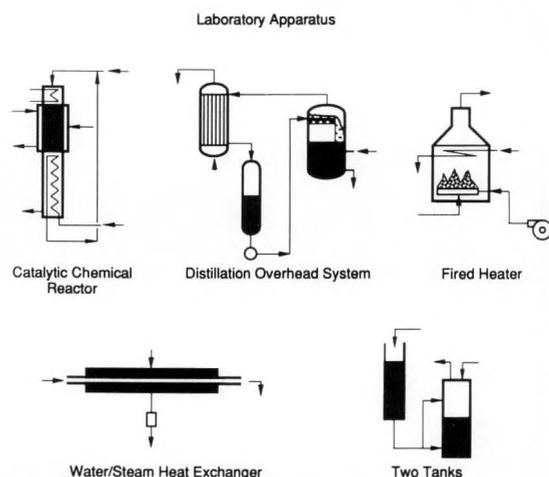


FIGURE 3. Simplified diagrams of laboratory apparatus used for student exercises on multiloop control systems.

convert them to engineering units, and display them in real time on the computer screen. They also connect output signals to valves and make changes in the flows with keyboard commands for the purpose of observing the process response to those flows. No computer programming is involved in any of this. Simplified diagrams of the apparatus in our laboratory used for such exercises are shown in Figure 3.

The students are subsequently introduced to UC SIGNAL, which they then use for the rest of the semester to develop control-system diagrams for the laboratory equipment and process simulations. Diagrams of some of our simulated processes are shown in Figure 4.

The sophistication of the control-system configurations in both activities evolves over the semester, starting with single feedback loops and moving on to cascades, feedforward, feedforward-feedback, 2 or 3 loops, gain scheduling, auctioneering, overrides, and variable structure systems. The experience is just right to whet their appetites for projects such as the one in Figure 1.

## CAPABILITIES OF UC SIGNAL

UC SIGNAL was designed to aid students in stating their ideas for a process control system as quickly as possible. Our intention was to make its workings as close as possible to what one would sketch on paper and as free as possible of the endless

paraphernalia and multi-volume user's manuals of the ultimate industrial system. It also had to be coordinated with UC ONLINE in both its "real-world" and its simulation modes. That we have done. The student sees UC SIGNAL working as follows:

### 1. The Process Diagram

This diagram (constructed by the instructor as described shortly) is displayed on the screen when the user loads it from a file. This is accomplished by making a selection from a pop-up menu; the program then prompts for the name of the file. All measurement transducers and valves are included in these diagrams. The menu selection is accomplished with a mouse-driven screen cursor, and the name of the file is entered through keyboard input. When activity is directed to a process simulation, the names of all measured and manipulated variables are set identical to those used in the simulation module (a responsibility of the instructor); the program prohibits the student from changing them. Nominal values of process variables may also be read in. When working with "real-world" laboratory apparatus, the naming of the variables and the designation of an I/O channel number is at the discretion of the student and may be changed at any time. The instructor has the option of supplying or not supplying the parameters needed to convert transducer signals to engineering units (*e.g.*, millivolts to degrees Celsius). So that they know how to do this, our students have to work these out early in the semester; we supply the parameters in the later part of the semester.

### 2. Making Links

One item in a pop-up menu is named LINK, and its selection with the mouse (or alternatively, with the keystroke L) enables the user to link any sensor with any actuator simply by first pointing to the sensor (the signal source) and then the actuator (the signal destination). A line representing the signal is immediately drawn on the screen without the user having to specify its route. The line is drawn to avoid all objects on the screen, with the exception that crossing of other signal paths and process streams is permitted. Using the same protocol, links can be made from an output of a control element (described shortly) to the input of another, or from any point on a signal to an input of an element or actuator. If the automatic signal routing is found inconvenient, the signal path can be rerouted. The signal can also be deleted and restored. Such "sketching" sets the skeleton of the loops. They have to be "fleshed out," however, with control elements before the structure can

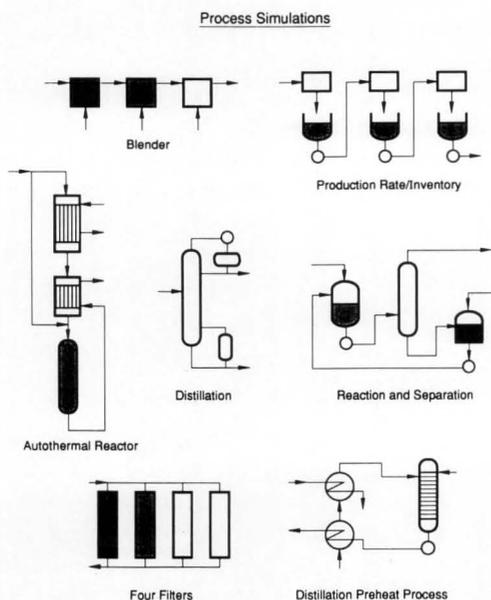


FIGURE 4. Simplified diagrams of simulated processes used for student exercises on multiloop control systems.

be considered complete.

### **3. Inserting Control Elements**

Any of a slate of control elements comprising a PID controller, a summer, a multiplier, a divider, high- and low-selection operators, a square root, and a lead-lag element can be selected from a pop-up menu and inserted at any point in any signal path. Linking among them can be accomplished in the manner just described. Elements can be exchanged with others if, for example, a multiplier was intended instead of a summer. They can be removed by elision and the signal restored automatically as it was before the element was inserted. And elements can be moved to any unoccupied location, with their signal links relocated automatically. It is also possible to place elements in "thin air" before links to them are made. Examples of the results of these operations are evident in the configuration shown in Figure 2.

The linking and inserting modes of the program are the workhorses of the system-configuration operation. The procedures used in these two modes are about as close as one can come to mimicking the pen strokes of an engineer as he sketches a system diagram on paper. And they are fast—just what we have been striving for. The procedures might even be considered as an advance over the pen-and-paper method because the signal paths are routed automatically. Most importantly, however, the visual relationship of control system to process is made clear—a relationship that can aid the designer in his system deliberations.

### **4. Setting Parameters and Interrogating Element Connectivity**

A certain amount of "bookkeeping" has to be attended to before the control system can be considered operational. Parameters have to be set to convert measurement signals to engineering units, high and low limits need setting in both controller and system variables, and controller tuning parameters and initial values of controller outputs have to be set. These tasks can be dispatched easily by entering numerical values in a pop-up parameter panel for every controller and system variable. To bring up the panel, the user simply picks the control element with the cursor. To help speed this data-input task, all high and low limits have been set to default values. The panels for the control elements have a field for accepting a name from the user. Usually, only controllers need to be specially named to aid the user in identifying the function of the controller. Any control elements not named by the user are

given arbitrary names by the program upon request or upon output of the configuration to a file.

The assignment of function to the three input signals of each controller should be checked by the user before completing the system synthesis. Pop-up information panels (which are brought to the screen by pointing to a controller input signal), state whether that signal is assigned as a measured variable in the control algorithm or assigned as a setpoint or a guard variable. Provision is available for interchanging functions if need be.

### **5. Saving the Configuration**

Complete information about the system (the graphical depiction, control element parameters, and linkages among the elements) can be saved to a file. That file can then be read back into UC SIGNAL again for the purpose of continuing work or to make modifications in the control system. A full-screen display of the system is recreated and a printed copy of the screen may be made at any time. The most important use of the file, however, is its use in communicating the control-system structure and content to UC ONLINE, the multiloop control program that executes the algorithms of the control elements placed in the system. All this can be done in a matter of seconds.

### **6. Features of the Instructor Mode**

The program incorporates facilities to aid the instructor in constructing diagrams of the laboratory apparatus or simulated process. Such facilities are available only to the instructor. Process diagrams can be constructed rapidly through assembly of a set of prepared symbols and objects, using the same graphics operations employed in the student mode of operation. Actuators and sensors can be placed, named, and "fixed" into position so that they are unmodifiable by the student. These "diagram" files that the instructor creates are those that are presented to the student; the diagrams appear on the screen when the files are called up by UC SIGNAL. Figure 1 is such a diagram.

## **CLOSING COMMENTS**

The thrust of our endeavors in developing UC SIGNAL and UC ONLINE is to open up opportunities for students to exercise their creative abilities in control-system synthesis. Without a facile and unfettered means of stating a proposed structure and without a means for demonstrating the workability of that structure, there would be little hope of achieving that goal. We now have those capabilities, and

through a carefully-crafted sequence of examples and encounters with various types of control-system substructures, one can expect to build in the students an expertise in control-system synthesis barely imagined just a few years ago. When we add to that the enthusiasm displayed by students in meeting such challenges, we are confident that we are getting better at this enterprise of engineering education.

## REFERENCES

1. Foss, A.S., "UC ONLINE: Berkeley's Multiloop Computer Control Program," *Chem. Eng. Ed.*, **21**, 122 (1987) □

## ChE book review

### CHEMICAL REACTOR ANALYSIS AND DESIGN, *Second Edition*

by G.F. Froment and K.B. Bischoff

John Wiley & Sons, Inc., 1 Wiley Drive, Somerset, NJ 08875-1271; 664 pages, \$59.95 (1990)

#### Reviewed by

Edmund G. Seebauer

University of Illinois, Urbana

Overall, I found this book to be quite suitable for a graduate-level course in reactor analysis, but too advanced for undergraduates. I disagree with the authors' statement in the Preface to the First Edition that the book may be used in a less-extensive treatment as a text for undergraduates. The chapters are not set up to clearly distinguish elementary from advanced material and there are relatively few simple, straightforward examples of elementary concepts that many undergraduates need in order to grasp the material. The style of writing is quite formal and compact. The overall level of mathematics is also too advanced for most undergraduates. In principle, such students have seen the matrix algebra, vector notation, and differential equations which are presented in this book. However, I believe that most undergraduates have little facility with these concepts, so that the mathematics becomes an impediment rather than a tool for understanding. The problems at the end of each chapter contain too few drill problems for simple concepts that undergraduates need in their homework assignments.

However, the above statements should not be taken as criticisms; the style and content of the text and problems are quite suitable for graduate students. The treatment of important concepts is up-to-

date and very well documented with literature references. Numerous summary paragraphs are included. While it might have been better to set these paragraphs off from the main body of the text, they are still quite useful. The table of symbols at the beginning of the book is also helpful. The detailed Table of Contents and the Author Index are excellent features, although the Subject Index is only average.

The treatment of chemical kinetics in Chapter 1 overreached itself in Example 1.4.4 and Section 1.6. The book does not pretend to be a text in physical chemistry (and rightly so). Hence, I found the treatment of transition state theory and the Lindemann mechanism to be so cursory as to be confusing. I would have mentioned these concepts in passing with only two or three sentences.

On the whole, however, it is a fine book. □

### AN INTRODUCTION TO RHEOLOGY

by H.A. Barnes, J.F. Hutton, and K. Walters

Elsevier Science Publishers B.V., Amsterdam, The Netherlands; \$100 hardbound, \$65.75 paperback (1989)

#### Reviewed by

Charles Manke

Wayne State University

In the preface to *An Introduction to Rheology*, the authors acknowledge that rheology is a "difficult subject" and that those seeking an introduction are often discouraged by the mathematical complexity of standard textbooks. This new book aims to provide an understandable introduction to rheology for newcomers to the field, particularly those without strong backgrounds in mathematics. The mathematical content of the book is minimized by a strategic organization of the subject material that defers consideration of continuum mechanics and constitutive equations (where mathematical complexity is unavoidable) until the final chapter. However, certain mathematical treatments (such as the tensor representation of stresses) are regarded as essential, and they are used throughout the book. Overall, this approach is effective, and the authors succeed in presenting a well-balanced, understandable overview of rheology without oversimplification or lack of rigor.

The early chapters of the book focus on rheological phenomena, with individual chapters devoted to non-Newtonian viscosity, linear viscoelasticity, normal stresses, and extensional flow. Here the reader is introduced to the nature and origins of rheological

*Continued on page 172.*

# IT GOES WITHOUT SAYING

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I never liked lectures as a student. Regardless of the subject or the lecturer I could never keep my attention from wandering, and even when I thought I was learning something I usually discovered later that I really hadn't gotten it. I like lectures even less as a teacher; I consider myself a pretty good lecturer, but the inevitable sea of glazed eyes in class and the subsequent questions in my office about things I taught explicitly have convinced me that I'm not accomplishing that much when I stand up and talk at students for fifty minutes.

The fact is that what routinely goes on in most college classes is not teaching and learning, but stenography: professor transcribes notes from notebook to chalkboard, students transcribe from chalkboard back to notebook. Even if the notes are supplemented with all sorts of insightful commentary, research shows that students in lectures generally retain a reasonable percentage only of what they hear in the first ten minutes and relatively little of anything that happens thereafter. They really only learn by thinking and doing, not watching and listening. And so I've been spending a growing amount of my time lately seeking ways to shift the focus from me to them during class.

For example, here is an in-class exercise I used in our second-semester sophomore course on chemical process analysis, just after we derived the transient open-system energy balance equation. (The exercise could equally well be used in the junior transport course.) I had the class divide themselves into groups of three at their seats and presented a series of problems. After I posed a problem I would give the groups some time to work on it (rarely enough to get a complete solution, often only enough to get started), then stop them and either present my solution or call on one or two of the groups to present as much as they had gotten. Here's how it went—my questions and comments to the class are in italics.

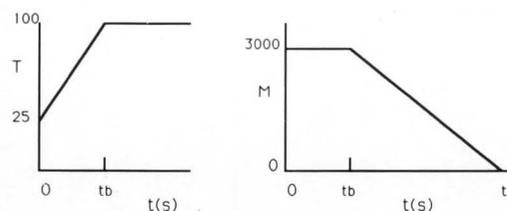
- *I'm going to ask you several questions about a teakettle filled with water. In answering them, you'll need the heat capacity of liquid water (J/g·°C) and the heat of*

*vaporization (J/g). Take a moment and come up with round-number estimates of these quantities.* (They did, and we then agreed to use 4 J/g·°C and 2000 J/g in our calculations.)

- *OK. Now, suppose we put the kettle on the stove and crank the burner up to maximum heat. Get me a rough estimate of the rate of heat input (kW) to the water in the kettle. Work in your groups—three people talking, one writing. Go.*

Initially there was bafflement, as this was anything but a well-defined problem. Some groups figured out that they would have to come up with estimates of how much water a typical teakettle holds and how long it takes to bring a full one to a boil, and others just scratched their heads. I let them go at it for a few minutes, then gave hints about the required information and let them resume. Then I stopped them and we reached consensus that a typical kettle holds about three liters or 3000 g of water, and it takes about five minutes to heat the water from room temperature (assume 25°C) to 100°C, which translates to a heat input of about 3 kW. (Group estimates in class ranged from 1.5 to 7 kW, a respectable range.)

- *So that means I've got to pay the electric company for 3 kW, right?* (Wrong! Only a fraction of the heat output from the burner goes into the water—I'm using considerably more than 3 kW.)
- *Where does the additional heat go?* (Into the kettle itself, the stove, and the room air.)
- *All right—let's agree that our system initially consists of 3 kg of water at 25°C and we are adding heat to it at a constant rate of 3 kW. My plan is to leave the kettle on the burner until there's no more water left in it. The next question is, if the system is the water in the kettle, which system variables change with time?* (T and M, the temperature and mass of the water.)
- *Take about 30 seconds and sketch plots of T vs. t and M vs. t.*



The class and I agreed that we couldn't be sure without more analysis that the ramps would be straight lines but that the curves would certainly look something like those two. I then asked them if they were quite sure that the M vs. T plot would be horizontal up to t<sub>b</sub>, and after a short time it occurred to several of them that pre-boiling evaporation would lead to a slight decrease in M. We

agreed to neglect this effect in our analysis, and then reached consensus that the mass-time variation would be described by the transient mass balance

$$\frac{dM}{dt} = -\dot{m}_{\text{out}}$$

and the temperature-time variation by the transient energy balance equation we had just derived in the last class

$$\frac{dU}{dt} = Q - \dot{m}_{\text{out}} \hat{H}_{\text{out}}$$

(input, kinetic and potential energy, and shaft work terms having been dropped). In these equations  $\dot{m}_{\text{out}}$  (g/s) is the rate of evaporation,  $U$  (J) is the total internal energy of the water in the kettle, and  $\hat{H}_{\text{out}}$  (J/g) is the specific enthalpy of the vapor.

In the next series of exercises, the groups concluded or were led to conclude that the periods before and after boiling commences must be analyzed separately, and that for the first phase of the process, (1)  $\dot{m}_{\text{out}} = 0$ , (2)  $M$  is constant, and (3) provided that the heat capacity  $C_v$  is constant,  $U = MC_v(T - T_{\text{ref}})$ . The last result harked back to material in the stoichiometry course that they had not seen for months, and we spent a little time reviewing it.

• **Now use all that to simplify the energy balance.**

I expected them to jump immediately to

$$\frac{dU}{dt} = MC_v \frac{dT}{dt} = Q$$

Instead, I got blank stares, which puzzled me but should not have. This transition from  $dU/dt$  to  $dT/dt$  is a trivial application of the chain rule for differentiation, which I've used so much I no longer think about it. They had never seen it outside of last year's calculus class, however, where it was taught abstractly and didn't mean anything to them. Once I figured out what was going on (after some unproductive knee-jerk chastising on the order of "Haven't any of you seen this stuff before?"), I backtracked and gave them a two-minute calculus refresher that might have been the most valuable thing they got in the hour. Then they went back, derived the equation, substituted for  $MC_v$  and  $Q$ , integrated to solve for  $T(t)$ , and confirmed that it takes 300 seconds for the water to reach the boiling point.

We then looked at the period  $t > 300$  s. I wrote the energy balance equation again

$$\frac{dU}{dt} = \frac{d}{dt}(M\hat{U}) = M \frac{d\hat{U}}{dt} = -\dot{m}_{\text{out}} \hat{H}_{\text{out}} + Q$$

• **Right?**

All of them bought it, but being used to my tricks they weren't too surprised when I announced "Wrong!" I gave them a moment to figure out the error, and it finally occurred to several of them that  $M$  is also a variable and the long-forgotten product rule for differentiation was required. I then wrote the correct formula:

$$\frac{dU}{dt} = \frac{d}{dt}(M\hat{U}) = M \frac{d\hat{U}}{dt} + \hat{U} \frac{dM}{dt} = -\dot{m}_{\text{out}} \hat{H}_{\text{out}} + Q$$

This equation baffled them completely—they had not previously encountered one with two derivatives in it. I asked if anyone could figure out how to get rid of one of them; no one could, so I pointed to the material balance equation still up on the board and substituted  $-\dot{m}_{\text{out}}$  for

$dM/dt$  to arrive at

$$M \frac{d\hat{U}}{dt} = -\dot{m}_{\text{out}} (\hat{H}_{\text{out}} - \hat{U}) + Q$$

It only remained to lead them to the conclusions that (1)  $\hat{U}$ , the specific internal energy of liquid water at 100°C, is constant, so that the derivative drops out, and (2) provided that

$$\hat{U} = (\hat{H} - P\hat{V}) \approx \hat{H}$$

for liquid water at 100°C (which I convinced them is the case by pulling values of  $\hat{U}$  and  $\hat{H}$  from the steam table), the final result for the energy balance is the intuitive one that

$$Q \approx \dot{m}_{\text{out}} \left[ \hat{H}_{\text{H}_2\text{O}(v, 100^\circ\text{C})} - \hat{H}_{\text{H}_2\text{O}(l, 100^\circ\text{C})} \right] = \dot{m}_{\text{out}} \Delta \hat{H}_v$$

Thus, we could finally calculate the rate of evaporation as

$$\dot{m}_{\text{out}} \approx Q / \Delta \hat{H}_v \approx [3000 \text{ J/s}] / [2000 \text{ J/g}] = 1.5 \text{ g/s}$$

and the time for all the water to evaporate as  $(3000 \text{ g}) / (1.5 \text{ g/s}) = 2000 \text{ s} = 33.3$  minutes. All of the values on the plots of  $T$  vs.  $t$  and  $M$  vs.  $t$  could now be filled in, which I did. I ended with a short review of everything we had done.

This exercise covered several important concepts in a variety of topics, including transient material and energy balances, thermophysics, thermodynamics, applied calculus and differential equations, and order-of-magnitude estimation, and showed how to put the concepts together to analyze a familiar system. It took me a little over an hour to get through it—all of one class period and about a third of the next one.

Could I have covered the same material in less time by simply lecturing? Sure, but I don't think the students would have gotten much out of it. Many (perhaps most) would have tuned out early in the lecture; others would have dutifully copied down whatever I wrote on the board but few would have understood enough of it to be able to use it on a slightly different problem. As it was, though, most of them stayed actively involved throughout the presentation (it's hard to hide in a group of three); they worried about the problems I wanted them to worry about, and after trying and sometimes failing to solve them, listened intently to hear what they should have done. When I later gave homework problems that required the use of similar analyses they did extremely well on them, and they also did much better on related test questions than I believe a normally taught class would have done. In short, they learned the material.

It isn't necessary to do something like this every class period—in fact, I'm not sure it would be desirable or even possible to do that. However, as a break from the usual straight lecture format, it's worked well for me every time I've tried it. Check it out for yourself. □

# A NOVEL FRESHMAN CLASS TO INTRODUCE CHE CONCEPTS AND OPPORTUNITIES

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One goal of this elective class is to attract students into our program by introducing them to the roles that chemical engineers play in a variety of industries. Our objective is a balanced presentation of the glamour and the challenges involved. We also hope to retain the interest of students who have already selected chemical engineering by allowing them to take a class in their major at the end of the freshman, rather than the sophomore, year.

Another goal of perhaps even greater importance is to provide a perspective for subsequent specialized classes. Students will have a better appreciation for courses such as kinetics and thermodynamics if they see "how it all fits together" at the beginning of their program instead of during the senior design course.

Outlines from the first two class offerings are shown in Table 1. The class is taught in 8-hour modules, with each module emphasizing a particular industry. Selected processes for each industry are discussed in detail (for approximately two hours), and the discussion includes product applications and demand, raw materials, and key process steps. Technical and ethical concepts are presented in the context of each process. We were unable to find a text that takes this approach, so we make extensive use of handouts (see list of references). Plant visits, videos, and guest speakers are used to provide a more complete picture of each industry. Homework is assigned, and students are quizzed on the material in each module. Projects with oral and written reports allow students to independently investigate topical problems. About six hours of class time is allotted for the oral presentations (ten to fifteen minutes per student).

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The class has been very successful despite the tight schedule of required classes faced by our freshmen engineering students. The first- and second-year enrollments of 20 and 24 students, respectively, represented about half of the freshmen who declared a chemical engineering major. A dramatic increase in department enrollment over the last two years cannot be solely attributed to student response to our class, but that response has been overwhelmingly favorable.

The students especially enjoyed the plant visits and the term projects—those parts of the class that are most different from the standard freshman-year curriculum. An interesting qualitative observation is that interest in the co-op program seems greater among students who have taken this class. We are continuing to offer the class on an annual basis, and are working to build on our early success.

## PROCESS MODULES AND LECTURES

Selected process examples, described in the following paragraphs, illustrate our approach. We made a conscious effort to incorporate topics from fresh-

man chemistry classes and the news media in order to increase class participation.

As shown in Table 1, we began each class offering with a module on water and food processing. This allowed us to introduce processing concepts by using products familiar to the students. Water purification is straightforward and easy to comprehend. The video *Always Pure, Never Runs Dry* (American Water Works Association) illustrates the treatment steps and emphasizes the need for strict quality control. We discussed the need for water desalination that results from local imbalances of freshwater supply and demand in many parts of the world. The high cost of desalinated water (in spite of the free raw material) easily leads to a discussion of processing costs. Desalination provides a good conceptual example of how separation processes exploit

**TABLE 1**  
**Class Outline**

**Spring 1989**

**Introduction**

**Water and Food Processing**

- water desalination • coffee processing • corn processing (plant visit) • cooking and extrusion processes

**Health Care and Biotechnology**

- industrial enzymes • fuel alcohol • biomedical applications • penicillin and other pharmaceuticals (plant visit)

**Chemical Process Industries and Petroleum**

- discussion of the life history of a process plant from inception to commercial production; topics included process development and design, plant design, construction, start-up, and manufacturing (refinery visit).

**Electronics and Advanced Materials**

- production of metallurgical-grade silicon • microelectronics fabrication • engineering polymers • advanced materials for transportation and recreation

**Student Project Presentations**

**Spring 1990**

**Introduction**

**Water and Food Processing**

- water purification (plant visit) and desalination • dairy and oil-based consumer products (plant visit) • corn oil processing

**Monomers and Polymers**

- petroleum processing and monomer production • polymers for "pop" bottles (HDPE and PET) • recycling of plastics • polymers for water treatment (plant visit)

**Electronics and Inorganic Chemicals**

- air separation and uses for oxygen and nitrogen • safety considerations in  $\text{NH}_3$  and  $\text{HNO}_3$  production • electronic materials (sand to silicon to circuits) • developing replacements for chlorofluorocarbons

**Biotechnology**

- enzymes and sugar processing • antibiotic production (plant visit) • product recovery and purification • principles and applications of modern biotechnology

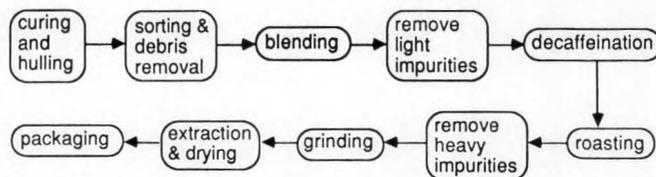
**Student Project Presentations**

differences between compounds. The most obvious difference between salt (solid) and water (liquid) cannot be directly exploited, as it can for separating sand and water. Other differences between salt and water lead to a discussion of evaporation, crystallization, and membrane processes, which provide examples for simple mass and energy balances. Safety considerations for human consumption provide the basis for a discussion of process control requirements for indirect vs. direct recycling.

Coffee is a familiar product that can be used for an in-class demonstration of extraction (for the coffee break). It is also a good example of a product that is sold based on qualitative end-user acceptance, rather than absolute specifications or performance in quantitative applications tests.

Separation processes required for the operations illustrated in Figure 1 include screening, density-dependent air classification, magnetic removal of iron, liquid extraction, and drying. The concept of open-ended design was illustrated by the many ways in which the process steps can be arranged. The rationale for selecting the process scheme shown in Figure 1 was also discussed. Roasting provides an introduction to poorly-characterized chemical reactions, as well as illustrating the need for tight process control to maintain product quality. It also provides an introduction to forced convective heat transfer and recycling for energy conservation. Finally, product safety and environmental concerns associated with methylene chloride were discussed.

Corn oil is another common product that can be used to illustrate many concepts. Although it is a premium product, corn oil is present in dried corn at low levels (about 5%) and is primarily a byproduct of starch production. The publication *Corn Oil*, distributed by the Corn Refiner's Association, provides a clear discussion of the processing steps involved and their effects on various aspects of product quality. The production of crude corn oil was used to illustrate grinding, centrifugal separation, oil expression, and solvent extraction. The latter process was used to introduce distribution coefficients and solvent selection criteria such as flammability, toxicity, and volatility. Corn oil refining removes components that



**Figure 1.** Steps in coffee processing.

adversely affect taste and/or appearance. Refining steps include degumming (centrifugation of precipitated phospholipids), removal of fatty acids as sodium salts, removal of color bodies by adsorption, winterization (crystallization of waxes), and removal of odor components using vacuum distillation with steam stripping. The degumming and winterization steps are of special interest because the undesirable properties of phospholipids (gumming in hot water) and waxes (crystallization in the refrigerator) are exploited to remove them from the crude oil. Due to the similarity in many of the operations, corn oil refining provides a good lead-in to crude oil processing (see below).

The "Monomers and Polymers" module had as its theme the production and disposal of plastic beverage containers. We began with a discussion of crude oil processing and the production of precursors such as ethylene and p-xylene. After considering the reactions used to produce ethylene glycol and terephthalic acid, we used high-density polyethylene and polyethylene terephthalate as examples of addition and condensation polymers, respectively. The importance of molecular weight and crystallinity was discussed in the context of bottle fabrication. Polymer recycling was used to introduce the concepts of resource recovery and waste minimization. We compared the fuel value of the bottles to the energy expended in their production and discussed problems involved in bottle collection and segregation by composition.

The penicillin process was used to illustrate key steps in product/process development:

- 1) *discover (natural) or create product*
- 2) *select organism (catalyst)*
- 3) *optimize process conditions to maximize productivity*
- 4) *modify organism (catalyst) to increase productivity*
- 5) *develop separation/purification process*
- 6) *iterate on steps 3, 4, and 5 to maximize overall process efficiency*

Portions of a NOVA film ("Rise of a Wonder Drug") were used to il-

lustrate the many disciplines required to develop a commercial process. Key contributions from chemical engineers in media sterilization, efficient supply of sterile air, optimization of fermentation parameters, and penicillin recovery and purification were highlighted. As part of the last item, we discussed the major contribution of product recovery to the total product cost, as well as how the multi-step purification scheme affects the overall penicillin yield.

We discussed the production of electronic-grade

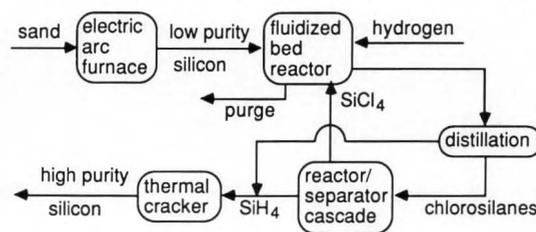


Figure 2. Block diagram of silicon purification.

TABLE 2  
Video Tapes (VHS) Used in the Class<sup>1</sup>

TITLE	DESCRIPTION	PRODUCER (YEAR)	TIME
Oil	oil and chemical industry	Current Affairs Multimedia (1990)	18 min
Out of the Air I	air separations, applications of N <sub>2</sub> and O <sub>2</sub>	Films for Humanities and Sciences (1987)	20 min
Out of the Air II	manufacture of ammonia, nitric acid	Films for Humanities and Sciences (1987)	20 min
Genetic Engineering: The Nature of Change	genetic engineering, especially for plants	Monsanto	16 min
Ways with Coal	combustion efficiency, alternate fuels, coke	Films for Humanities and Sciences (1987)	20 min
Polyethylene	polymerization, applications of polymers	Films for Humanities and Sciences (1987)	20 min
The Chemical Engineer and Biotechnology	roles of ChE's in processing and purification	AICHe (1988)	10 min
Opportunities in Advanced Materials	roles of ChE's in a variety of industries	AICHe (1988)	15 min
Opportunities in Environmental Protection	waste-water treatment, hazardous waste issues, biodegradation	AICHe (1989)	25 min
The New Engineers	opportunities in engineering, some ChE	National Science Foundation	27 min
Always Pure - Never Runs Dry	drinking-water treatment	American Water Works Association	17 min
The Rise of a Wonder Drug	history of penicillin development	NOVA	58 min

<sup>1</sup> Films can be rented or borrowed from university film libraries. Many free videos are available from Modern Talking Picture Service (5000 Park Street North, St. Petersburg, FL 33709-9989.)

silicon from sand in both class offerings. This process serves as an introduction to the microelectronics industry and the problems associated with preparing ultrapure materials. Solids purification is an unfamiliar concept to the students, so the purification strategy was carefully outlined. The process (see Figure 2) first converts solid  $\text{SiO}_2$  to liquid, metallurgical-grade Si. Liquid silicon is solidified and reacted with hydrogen and  $\text{SiCl}_4$  to form Si-containing gaseous molecules ( $\text{SiH}_x\text{Cl}_{4-x}$ ).  $\text{SiH}_4$  is removed and the remaining  $\text{SiH}_x\text{Cl}_{4-x}$  is converted to  $\text{SiH}_4$  and  $\text{SiCl}_4$  in a series of disproportionation reactor/separators.  $\text{SiCl}_4$  is recycled, and the combined  $\text{SiH}_4$  stream is thermally cracked to deposit electronic-grade silicon on a seed crystal. Impurities are removed in a purge from the fluidized-bed reactor, as well as during replacement of ion exchange resin in the disproportionation reactors. Methods of gas/solid contacting were discussed, and fluidization was introduced. Recycle of unused reactants was emphasized. This process provides examples of heterogeneous chemical reactor technology, as well as many examples of phase-change operations such as melting, distillation, and chemical vapor deposition.

### GUEST SPEAKERS AND VIDEOS

Three lecturers were used during the first class offering. Each of them lectured on areas that they were familiar with, and their expertise was supplemented by an industrial speaker on biomedical applications. Multiple viewpoints are useful for providing perspective, but it is important to coordinate the

material and the level at which it is presented.

In the second offering there was one primary lecturer, with guest lectures on two topics. Added perspective, as well as illustration of laboratory experiments and plant equipment, was provided by videotapes. Many videotapes are not geared towards technical audiences, so it is important to screen them before use. We have compiled a list of useful videos in Table 2. AIChE career guidance tapes (e.g., "Biotechnology" and "Advanced Materials") are very good because they focus on what individual chemical engineers do in various industries. The "Chemistry in Action" series (distributed by Films for the Humanities and Sciences) focuses on specific process industries. Two of these videos ("Out of the Air: 1 and 2") were used as the basis for lectures on air separation, uses of oxygen and nitrogen, sulfuric acid production, and production of ammonia and nitric acid. The latter topic provided the focus for a discussion of process safety considerations.

### PLANT VISITS

Plant visits provide a sense of the scale of operations involved, illustrate production processes discussed in class, and give students a chance to interact with practicing engineers. We visited a variety of facilities and working environments (see Table 3) because different students have different interests, and because we wanted to give a balanced perspective. In selecting trips, it is important to remember that freshmen have had limited exposure to the chemical industry. For example, students are impressed by the size and complexity of a petroleum refinery, but have a hard time following what is going on in all of the closed process units. Examination of flow rates and temperatures on a simulator in the control room helps to bring the process down to size. Samples that illustrate the conversion of raw materials (through a variety of intermediates) to final products are especially helpful for process visualization.

Student benefits from a plant visit can be improved by prior preparation. We recommend discussing the tour with the prospective host to be sure that it will meet class needs. In this regard, it is important to note that freshmen are even more interested in what they would do if they worked at a particular plant than they are in the various process steps involved. The learning experience from a tour can be increased by discussing the process in class prior to the trip, and by discussing in a quiet location what will be observed in noisy areas during the

**TABLE 3**  
**Plant Visits**

- **Evanston Water Treatment Plant**, Evanston, IL  
*Pumping, water treatment (chlorination and flocculation), filtration, and quality control*
- **American Maize Corporation**, Hammond, IN  
*Corn wet milling for starch recovery, waste treatment, and starch packaging operations*
- **Kraft General Foods**, Glenview, IL  
*Pilot plant. Dairy products, salad dressings, emulsions, and mixing operations*
- **Abbott Laboratories**, North Chicago and Abbott Park, IL  
*1989, Abbott video and general tour of fermentation, formulation, tableting and filling areas with guides from public relations. 1990, Tour of fermentation plant and fermentation and recovery pilot plants with practicing engineers*
- **Mobil Oil Corporation**, Joliet, IL  
*Refinery bus tour and control room visit*
- **Nalco Chemical Company**, Chicago, IL  
*Synthesis and formulation of water treatment chemicals. Pilot plant and production facilities*

plant tour. It is also useful to prepare students for the noises and smells that will be encountered. The noises and smells of a chemical plant disenchant some of our students, but others react very positively to the production environment.

Our most successful visit was one to the Kraft General Foods Pilot Plant. All of the products (ice cream, mayonnaise, and oil-free salad dressings) were familiar to the students. The changes taking place in each process unit were readily apparent from the differences between raw material and product samples, and the process steps were easy to follow due to the small unit size. Recent engineering graduates discussed their duties and accomplishments at selected process units during the tour, as well as at a subsequent question-and-answer session. Student enthusiasm during the bus ride back to campus resulted in questions (which were addressed in a follow-up lecture) about the differences between batch and continuous processes and about mayonnaise manufacture.

## STUDENT PROJECTS

Group projects are an important component of the course. The primary project objective is to have students analyze a particular topic in depth, including technical, societal, and market considerations. Selection of topical projects increases student interest, and shows them how chemical engineers can contribute to the solution of current problems. Students are not prepared for detailed process design. However, they can discuss limitations in current technology, as well as the trade-offs between conflicting goals. They can also obtain an appreciation for the large number of possible solutions to complex problems. Additional project objectives are to introduce students to the technical library, provide experience working in groups, and improve oral and written communication skills. Group papers were prepared, and all students participated in oral presentations of the group's findings. Feedback was provided by student and faculty questions and by faculty critiques. Small prizes were awarded for the best oral reports, as selected by student balloting.

Project topics for the first year, along with some of the concerns addressed, are shown in Table 4. The students had a little trouble getting started on these open-ended projects, but periodic progress meetings with faculty helped to provide direction. All of the students put a lot of effort into the projects, and many independently found reference material at other libraries or government agencies. The mate-

rial presented in the written reports exceeded our expectations. There was some confusion about specific process steps, but the students showed a good appreciation for the interaction of technological and societal concerns. Student projects also provide a good way to obtain background material for subsequent class offerings. For example, lectures in 1990 on polymers for pop bottles and chlorofluorocarbon replacements were based in part on 1989 student-project reports and references.

The project theme for the second year was alternatives to petroleum for production of energy and chemical feedstocks. A homework assignment on petroleum consumption and imports got students into the library early in the quarter. Each group was also required to hand in a list of references soon after project assignments were made. Periodic meetings between each group and the instructor helped to keep the students from getting lost. To increase interest in the oral reports, each of the three groups working on a topic was asked to focus on a particular aspect of the problem, as indicated in Table 4. As for the first year, a wide range of organizational, speaking, and writing abilities was demonstrated by the class, suggesting that additional practice in communication skills is required.

**TABLE 4**  
**Term Project Topics**

### *Spring 1989*

#### **Life Support and Environmental Control in Space**

- requirements of a life-support system
- alternative methods for meeting the needs
- selection of environmental control system configuration

#### **Polymeric Packaging (Polymers and Pop Bottles)**

- requirements for food packaging, especially pop bottles
- relative advantages of different packaging materials
- PET properties and manufacturing process
- recycling and biodegradation

#### **Phasing out Chlorofluorocarbons (CFCs)**

- effects of CFCs on ozone degradation
- present uses for CFCs; key properties for each use
- reduction of CFC emissions
- technology required for CFC replacement

### *Spring 1990*

#### **Coal as a Supplement for Petroleum**

- use of coal for electrical energy generation
- production of liquid fuels from coal
- production of chemical feedstocks from coal

#### **Biomass as a Supplement for Petroleum**

- combustion of waste and trees to generate electricity
- production of liquid fuels and chemicals from grain
- production of liquid fuels and chemicals from waste

#### **Nuclear Power as a Supplement for Petroleum**

- expanded use of light-water reactors
- nuclear waste disposal practices
- fusion and fast breeder reactors

## GRADING

We rejected P/N grading because of concerns that it would reduce student incentives to complete class assignments. Grades were based on four 30-minute quizzes (30%), weekly homework assignments (30%), and the oral (10%) and written (30%) project reports. Homework and quizzes included quantitative and discussion questions. Quiz formulation and grading is challenging because the students have a wide range of mathematics and chemistry backgrounds. An example quiz is shown in Table 5.

## ACKNOWLEDGEMENTS

We would like to thank Bernie Wendrow for his help in teaching the class in the spring of 1989. We would also like to thank all of the companies listed in Table 3 that made our plant visits so successful.

## REFERENCE MATERIALS

### Chemical Process Industries

"Synthetic Ammonia," in *Shreve's Chemical Process Industries*, R.N. Shreve and G. T. Austin, McGraw-Hill, New York (1984)

TABLE 5

Quiz: Electronics and Inorganic Chemicals  
(Closed Book and Notes)

- (35) Safety is a major concern in the chemical industry and for chemical engineers: List three general types of hazards encountered in chemical processing. For each type of hazard:
  - give two specific examples of the hazard taken from processes discussed in class, and
  - briefly describe (in general terms or with a specific example) one way in which that type of hazard can be mitigated.
- (35) Purity is essential in electronic materials.
  - Consider the many steps involved in taking metallurgical silicon to fabricated electronic components. Briefly discuss three steps in the process that can lead to contamination or product degradation, and for each note the type of contamination or degradation involved.
  - Briefly discuss the relative purity requirements of electronic components as compared to food products. Recall that refined corn oil contains 98.8% triglycerides.
- (30) The largest use for CFCs is in refrigeration and air conditioning systems. The physical properties are listed below for several replacement candidates.
  - Discuss which candidate is the most promising replacement and why.
  - List (with no discussion) three other properties of the compounds that would have to be considered in selecting a replacement for CFCs.

Compound	A	B	C	D	E
Boiling point at 1 atmosphere (°C)	-30	-30	-30	20	20
Boiling point at 10 atmospheres (°C)	20	40	40	60	60
Heat of vaporization (kcal/mol)	12	6	12	12	6

Speight, J.G., "Petroleum Processing" and "Petroleum Products," in *McGraw-Hill Encyclopedia of Science and Technology*, McGraw-Hill, New York (1987)

### Energy and the Environment

- Makhijani, Arjun, A. Bickel, and Annie Makhijani, "Beyond the Montreal Protocol: Still Working on the Ozone Hole," *Technology Review*, p. 53, May/June (1990)
- MacKerron, C.B., "Chemical Firms Search for Ozone-Saving Compounds," *Chem. Eng.*, p. 22, January 18 (1988)
- Stolarski, R.S., "The Antarctic Ozone Hole," *Scientific American*, **258**, 30, January (1988)
- Taylor, J.J., "Improved and Safer Nuclear Power," *Science*, **244**, 318 (1989)

### Health Care and Biotechnology

- Gebhart, F., "GEN's 10 Prime Areas for Biotech Commercialization," *Genetic Engineering News*, p. 7, January (1990)
- Hopwood, D.A., "The Genetic Programming of Industrial Microorganisms," *Scientific American*, **245**, 90, September (1981)
- Langlykke, A.F., "The Engineer and the Biologist," in *The History of Penicillin Production*, A.L. Elder, Ed., *Chem. Eng. Prog. Symp. Series No. 100*, Ch. 11, p 91 (1970)
- Rosen, C.-G., "Biotechnology: It's Time to Scale Up and Commercialize," *CHEMTECH*, p. 612, October (1987)
- Wick, C.B., "Biodegradation Will Play Key Role In Hazardous Waste Treatment in '90s," *Genetic Engineering News*, p. 5, May (1990)

### Materials

- Pogge, H.B., "Material Aspects of Semiconductors," *CHEMTECH*, p. 497, August (1985)
- Hart, A.M., B.C. Peters, J.H. Plonka, W.H. Werst, Jr., and J.M. Macki, "Advanced Ceramic Opportunities: A Review," *Chem. Eng. Progress*, p. 32, April (1989)
- Larrabee, G.B., "ChE Challenge: Microelectronics," *Chemical Engineering*, p. 51, June (1985)
- Dolde, M.E., "Sporting Plastics," *CHEMTECH*, p. 523, September (1988)
- Thayer, A.M., "Solid Waste Concerns Spur Plastic Recycling Efforts," *Chem. and Eng. News*, p. 7, January (1989)
- Thayer, A.M., "Degradable Plastics Generate Controversy in Solid Waste Issues," *Chem. and Eng. News*, p. 7, June (1990)
- Voss, D., "Plastics Recycling: New Bottles for Old," *Chem Eng. Progress*, p. 67, October (1989)

### Water and Food Processing

- Cammarn, S.R., T.J. Lange, and G.D. Beckett, "Continuous Fluidized-Bed Roasting," *Chem. Eng. Progress*, p. 40, June (1990)
- Giacone, J., and S.J. Sommerfeld, "The Food Industry in the Year 2000," *Chem. Eng. Progress*, p. 19, May (1988)
- "Nutritive Sweeteners from Corn," "Corn Starch," and "Corn Oil," booklets available from Corn Refiners Association, 1001 Connecticut Ave. NW, Washington, DC 20036

### Other Topics and General Sources

- American Chemical Society pamphlets including "Pesticides," "Biotechnology," "Acid Rain," "Ground Water," "Hazardous Waste," and "Chemical Risk: A Primer." Contact ACS, Dept. of Gov. Relations and Science Policy, 1155 Sixteenth St. NW, Washington, DC 20036
- AICHe pamphlets "The Expanding Domain of Chemical Engineering" and "Careers in Chemical Engineering," from AICHe, 345 E. 47th St., New York, NY 10017
- Travis, C.C., S.A. Richter, E.A.C. Crouch, R. Wilson, and E.D. Klemma, "Risk and Regulation," *CHEMTECH*, p. 478 (1987)
- Kirk-Othmer Encyclopedia of Chemical Technology*, Wiley, New York (1984) □

# ERRORS

## *A Rich Source of Problems and Examples<sup>1</sup>*

WALLACE B. WHITING  
West Virginia University  
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**E**ngineering instructors are constantly on the lookout for new and better problems and examples to use in homework assignments, lectures, or examinations. Yet a rich source of these problems is generally overlooked: the numerous errors in textbooks or published articles, and even our own assignments and examination questions. Problems developed from errors simulate real-world situations in which engineers must catch and correct their own and other people's errors. They can also show students that real engineering problems are open-ended—not well-posed mathematical situations that can be solved simply by plugging new numbers into an old equation.

### WHY USE PEOPLE'S MISTAKES?

Engineers make mistakes. In fact, Petroski<sup>[1]</sup> presents a convincing case that errors are the driving force for engineering advances. Do engineering students typically confront this idea in school? Would they be more interested in their courses and would they more fully comprehend their future profession if they did?

Many of us try to prepare homework assignments and examinations that are straightforward: straightforward to write, straightforward to do, straightforward to grade. In fact, one criterion often espoused for a well-written test question is that the instructor can anticipate all possible student responses. The

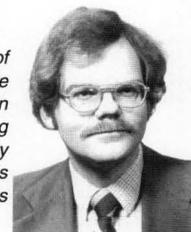
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***Honest errors appearing in textbooks, articles, and instructor-generated assignments can serve as meaningful vehicles of instruction.***

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<sup>1</sup> This material was presented at the 1987 ASEE Annual Conference. Reference 2 is a more complete version of the paper.

**Wallace B. Whiting, P.E.**, is Associate Professor of chemical engineering at West Virginia University, where he has taught for the past decade. He is active in ASEE and AIChE, and his research and teaching interests range from thermodynamics to process safety and process design. He welcomes dialogue on this and all of his articles. New homework assignments often grow out of such discussions.



strong bias toward generating questions with as few conceivable responses as possible can result in a simple mistake (typographical or otherwise) rendering a question "unanswerable." If we uncover such an error (usually during the grading process), we apologize to the students (or try to cover up) and discount the grade for that question. After all, it was not the students' fault that the instructor posed an impossible question. We wouldn't want them to think that engineering problems are sometimes ill-posed, that they can be frustrating, or that they may not have an answer. Or would we?

Textbooks and technical articles are full of errors. Some stem from the author's misconceptions and some are the result of inadequate proofreading. What happens to students faced with a homework assignment that (unknown to the course instructor) has a typographical error making the problem indeterminate? After much time and frustration the students finally give up, figuring that they will learn the solution in class. When the class meets, the instructor explains that the problem should have included an additional piece of information or a different equation, and if it had, it could be done in such-and-such a way. In a blaze of chalk dust, the solution to a *different problem* is presented, and the students dutifully write down this new question and answer. The same scenario may occur again and again, until the students are convinced that engineering problems can only be solved when they are presented in an error-free and well-posed form.

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*Good engineering textbooks take years to write but most still contain numerous errors, many of which may be typographical (and presumably will be corrected in subsequent printings). . . . Most instructors find that the difficulty is not in finding textbook errors, but in deciding what to do about them.*

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One cannot really avoid using errors as a source of problems and examples. The choice is only how they will be used and to what end.

## SOURCES OF ERRORS

Below are some examples of errors that I have used. The list is not meant to be exhaustive, it simply suggests where to look. More details are given elsewhere.<sup>[2]</sup>

### *Textbooks*

Good engineering textbooks take years to write but most still contain numerous errors, many of which may be typographical (and presumably will be corrected in subsequent printings). To show what kind of problems occur, I will describe some errors in first-rate engineering texts that I have used. (In the interest of the authors, I will not cite the references.) There are, of course, many other examples of errors. Most instructors find that the difficulty is not in finding textbook errors, but in deciding what to do about them.

**Missing Information** In one homework problem that I have used, the conversion of a reactor is omitted from the problem at the back of a chapter. Without this specification, the problem is indeterminate—there are more unknowns than the number of independent linear equations that can be derived to solve for them. The instructor may assign this problem, skimming the problem statement and the solution in the Solutions Manual to be sure that the problem is of an appropriate difficulty. However, the Solutions Manual uses an 80% single-pass conversion in the solution, even though this information is not in the problem statement (and cannot be inferred from the information that is given). When they attempt this homework problem, students give up after reaching varying levels of frustration. The instructor often doesn't notice the printing error until a student asks a question about it during class as the instructor is going over the problem.

**Corrected Printing Errors** Very popular texts often go through numerous printings and it is not uncommon for some errors to be eliminated but others to be added. An interesting situation can arise

when the instructor and the students have different printings of the same edition of the text. I have found three different versions of a problem in a text on numerical methods. In one version a printing error leads to a non-physical numerical answer; subsequently, an erroneous correction leads to yet a new problem. An incorrect assumption is made in the problem statement, but a footnote attempts to guide students to a correct solution. An additional misprint results in violation of the conservation of mass. Thus, the misfortune of the authors and the publisher of this fine textbook increases the richness of the problem several-fold, exposing the students to these concepts:

- Printers make mistakes
- Equations may have to be reformulated if certain assumptions are not valid
- Footnotes are important
- Complex or imaginary numbers may be an indication of errors in problem formulation or computer programming
- Material balances should always be checked

When I used the above problem in class, we ended up solving four different problems—the three flawed printed versions and the other "correct" version (which appears in none of the printings that I saw). The ensuing discussion of nonlinear equations, fluid mechanics, and problem-solving techniques lasted the entire class period and was one of the most worthwhile sessions of the semester.

**Deliberate Errors** Some textbook homework problems incorporate intentional errors. These problems range from reproductions of newspaper articles describing impossible processes to mis-specification of design variables. Students initially see such problems as "trick questions," but many problems incorporating deliberate errors provide ideal vehicles for teaching content and problem-solving skills.

For example, the "Ice Skating Problem," which appears in numerous thermodynamics texts, proposes that the pressure under the skate blade is great enough to lower the melting temperature of the ice to the ambient temperature. In this case, the thin layer of water that forms would lubricate the blade continuously, and this phenomenon would

explain the very low friction that is experienced in ice skating. One expects students to recognize that they can use the Clapeyron equation to determine the pressure required to melt the ice and that they need to make engineering approximations and assumptions about ambient conditions, skater weight, and contact between the skate blade and the ice surface. Overall this is a very good problem, but the answer given in some thermodynamics texts (and solution manuals) is wrong. When the problem is looked at in detail, the melting-point depression is but one of *several* factors contributing to the low friction that makes ice skating such an exhilarating experience. The students learn that often many different factors contribute to phenomena and that the first one they think of may not be one of the more significant ones. Perhaps equally important, students gain confidence in their own abilities when they think of additional factors, especially if the textbook ignores them.

**Difficult Written Passages** Often, technical writing is dense—difficult both to write and to comprehend. One particularly demanding type of writing is the process description. Even in a first course in chemical engineering, students are confronted with process flowsheets consisting of over a dozen units, a score of streams, and a recycle or two. Our students must be able to develop a flowsheet from a verbal description of a process. This is a skill that the students will need in their profession, and it is a common and effective teaching technique.

Many texts and articles include process descriptions. The problem is that the descriptions are often difficult to read and to comprehend. The numerous interconnections in the process and the often unfamiliar process units often confuse students. They immediately realize that the description is difficult, and some even suggest that they could write a better, clearer process description.

Although a convoluted written passage may not properly be called an "error," it demonstrates that even well-respected authors have limitations. Students can learn a great deal about engineering (as well as about technical writing) by being asked to decipher dense prose.

### **Other Books**

Engineering students read many books in their field other than their textbooks (or so we hope), and the errors in these references can also be a source of examples and problems. One example is a printing

error in the solution procedure for cubic equations in the *Chemical Engineers' Handbook*.<sup>131</sup> I have not used this particular example in class yet since I feel the students may become *too* frustrated when trying to use the method presented. Instead, I alert the students to the error and ask them to correct the equations in their copy of the handbook. By bringing the error to their attention and describing the frustration they might have experienced had they tried to use the erroneous equations, I hope that they will learn the importance of verifying printed information rather than simply assuming that it is correct.

### **Articles**

**Trade Journals** Many periodicals of this type are printed in a hurry and without peer review. As a result, it does not take long to find articles containing errors. I am especially fond of an article printed in *Consulting Engineer* entitled "Breakthrough! Electricity Without Fuel."<sup>141</sup> Reactions of engineers to this article are diverse. Some laugh when they read the title, realizing that it must be about a perpetual-motion machine, while others are puzzled by a simple sketch in the article showing how endless supplies of electricity can be obtained from the judicious and selective use of gravity.

As a first assignment in my graduate thermodynamics course, I give the students copies of this article and ask them to prepare short reports evaluating the process and proposing any improvements they would like to make. Many students with high grade-point averages suggest exotic process modifications backed up by "impressive" calculations. We spend an entire class period on this article alone, and the students learn much about the laws of thermodynamics and their consequences. They also become more confident in their own ability to think critically. (Note to the reader: If you get a copy of this article, please be sure to read the boxed items on the second page.)

**Research Journals** Anyone who has ever written an article, reviewed one, or read one, can see that research journals are a bounteous source of errors.

**Other** Newspapers and popular magazines often contain articles describing devices that could not possibly operate as described or data that are inconsistent. In the appropriate course, these can be fine sources of class problems.

### **Computer Programs**

Most of the effort in writing computer programs

is spent finding and correcting errors. Students quickly realize this during the first assignment. What they may not realize, however, is that most of their learning occurs during this debugging process. Some instructors have suggested that students should be required to debug each other's programs, but I have not tried this assignment, yet.

### ***Our Own Assignments!***

Instructors, mere mortals that we be, produce an abundance of flawed homework assignments and examination questions. While I do not suggest that we should be less diligent in trying to develop well-thought-out assignments, I do propose that some of our better problems may be those that have small, honest errors that make the problems more realistic and open-ended. There is, however, great danger in trying to introduce a trick error. Honest errors are more realistic, and they are certainly less upsetting to students.

### **HOW TO USE ERRORS**

Some of the ways that errors can be used have been mentioned in the foregoing paragraphs. The following is a brief summary of these approaches along with some additional techniques. I have found some of these methods useful; others I have only thought about using. Although I cannot claim that any of them are guaranteed to work, I believe that they can be effective, and I encourage experimentation with them.

***Assignments*** With the numerous printing and other errors in even the best textbooks, all of us have assigned (or soon will assign) a problem containing an error. Rather than an embarrassment, this is an *opportunity*. Instead of trying to minimize the error, the instructor can use it to explore the subject matter and help the students learn to ask appropriate questions. How far can one go in solving the stated problem? What minimum additional data are needed? What reasonable assumptions can be made about the missing parameters? Would it be expensive (or even feasible) to measure the missing values in a real situation? How might the solution to the problem differ for various assumptions about the missing data? How can errors be identified in the future? The list goes on and on.

***Classroom Examples*** Using errors can be challenging (and even intimidating) for both instructors and students. A good way to introduce this approach is to use an example in a lecture. In this controlled situation, students will be less frustrated than they

would when working on a problem at home. Some frustration is helpful, however. As in most circumstances, but especially when discussing errors, students must ask questions during the lecture or they will neither internalize concepts nor develop a strategy for dealing with errors. The instructor must be prepared for unexpected questions and be constantly aware of the students' need for structure and for meaningful notes from which to study after the class session is over. The questions that the instructor might ask, and the directions that the discussion may take, are similar to those described above under "Assignments." The difference is that the instructor has more control in a lecture format and that the students will encounter less frustration than they would if tackling the problem alone.

***Examination Questions*** Is it appropriate to use errors in examination questions? The answer is yes—maybe. An examination is not the ideal place to introduce students to errors in problem formulation, but it is a good place to use such problems once they have been introduced in one of the other ways described above. Only during an examination can the instructor be fairly certain that students will read what they have been asked to read and think about it.

***Projects*** It is probably impossible to develop a meaningful project assignment of any scope that does not contain some errors. And, in fact, this may be the most appropriate place for students to learn how to deal with errors. During a project students have time to think, explore, and try alternative solution methods. They need to be exposed to the realities and frustrations caused by engineering errors. The instructor must avoid formulating unrealistic or "trick" errors, however, lest the students view them as existing only in the pseudo-world of academia. Plenty of errors are inherent in most projects. The point is to deal with them as honest errors indicative of the real world of engineering.

### **DOES THE USE OF ERRORS WORK?**

I have no statistically valid or quantitative data to show that using errors improves the quality of instruction. I do, however, have anecdotal evidence that it stimulates students and gives them a new and more realistic viewpoint of their profession. As to the effectiveness of this technique, I can only suggest that it is worth a try. I have found it successful.

In any case, errors certainly are a rich and exciting source of problems and examples that can stimu-

late lively classroom discussion. They can also provide a model of an engineer (the instructor) solving an ill-defined engineering problem in real time.

## CONCLUSIONS

Honest errors appearing in textbooks, articles, and instructor-generated assignments can serve as meaningful vehicles of instruction. They demonstrate that engineering problems are often ill-posed, requiring frequent checks and creative problem-solving techniques. They thus help to prepare students for dealing with the many errors that they will inevitably encounter during their careers.

## ACKNOWLEDGEMENT

I would like to thank all those authors whose errors I have used. The high quality of the texts that I use make these errors all the more meaningful and useful. I hope others will feel free to use errors that they find in my published work as classroom examples.

## REFERENCES

1. Petroski, H., *To Engineer Is Human*, St. Martin's Press, New York (1985)
2. Whiting, W.B., "Textbook Errors: A Rich Source of Problems and Examples," 1987 ASEE Annual Conference Proceedings, Reno, June 1987, p 1631.
3. Perry, R.H., and C.H. Chilton, Editors, *Chemical Engineers' Handbook*, 5th ed., McGraw-Hill, New York (1973)
4. Dickens, R., "Breakthrough! Electricity Without Fuel," *Consulting Engineer*, p. 76, Sept. (1981) □

## ChE book review

### AN INTRODUCTION TO NUMERICAL METHODS FOR CHEMICAL ENGINEERS

by J. B. Riggs

Texas Tech University Press, Box 4139, Lubbock, TX 79409-4139; \$45 (cloth) (1988)

**Reviewed by**  
**Santosh K. Gupta**  
**Indian Institute of Technology; Kanpur, India**

The need for teaching a course in numerical techniques to undergraduate chemical engineers is being recognized more and more these days, and several schools have started offering such courses. As a result, a large number of textbooks have appeared in the area. However, only a few of them are addressed primarily to chemical engineering students. The book

by Riggs is thus very timely, and it is an excellent text. A floppy disc containing several programs is also included. It can be used to solve problems in the text as well as being used later.

Chapter 1 of the book gives an introduction to matrix operations and round-off and truncation errors. Chapter 2 treats algebraic equations, and the method of LU decomposition for solving linear equations is of particular importance. Regula falsi and Newton's method are used for non-linear equations. The treatment in Chapter 3 of the various finite difference approximations of the first and second derivatives is good. This is followed by cubic spline interpolation, as well as quadratures.

Chapter 4 presents techniques for solving initial value problems (ODE's and PDE's) using both implicit and explicit methods. Several software packages have been referred to for solving stiff ODE's. The presentation of finite difference methods as applied to PDE's in space and time is excellent.

In Chapter 5 the finite difference approximations are suitably used to obtain the recursion (SOR) relations for the governing differential equation and for the boundary points, and these are combined to effect a numerical solution for a boundary-value problem. Also, good examples are given on direct methods using the Thomas algorithm and shooting methods. The use of a finite element library routine (FEC) is shown through an example.

Chapter 7 deals with regression analysis of experimental data. Very useful and common examples on chemical kinetics are presented and the use of optimization is shown for non-linear regression.

Chapter 8 discusses how the homotopy method can be used to find the roots of nonlinear algebraic equations. This chapter also discusses some more-advanced examples.

The most fascinating feature of the book is that several illustrations and problems from various fields of chemical engineering (mass transfer, kinetics, thermodynamics, etc.) are discussed. In some cases, the limitations of the techniques are clearly explained and the methods to overcome the difficulties are presented. For example, systems of nonlinear equations arising out of material balances on a CFSTR are solved by Newton's method (Chapter 2), but in the case of extreme non-linearity they are converted to coupled ODE's constituting an IVP, and these, in turn, are solved using a powerful algorithm (LSODE)

*Continued on page 153.*

***EDITORIAL NOTE:***

*The following detachable pages describe some industrial employment opportunities for graduating chemical engineers. Please post the information in a conspicuous place for the benefit of your students, or distribute the pages to students who may be interested.*

*These companies have expressed a definite interest in hiring chemical engineers in the areas described, and we strongly encourage students seeking employment to respond as indicated.*

***Ray W. Fahien***

***Editor***

***Chemical Engineering Education***



# DOW CHEMICAL USA

University Relations  
Box 1713-CH  
Midland, MI 48674

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**REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED:** Nationwide

**HOW TO APPLY IF UNABLE TO SCHEDULE A CAMPUS INTERVIEW:** Send resume and letter to above address, stating your job interests and geographic preferences.

## ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS

### BS/MS

Functional Area	Degree Level	Major Hiring Locations
Design	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Process Engineering	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Manufacturing	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Research and Development	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Sales	BS,MS	Offices in over thirty major cities

### PhD

Fields of Special Interest	Tech Center Locations
Math Modeling	Michigan, Texas, California
Polymer Processing	Michigan, Texas, California, Ohio
Polymer Characterization	Michigan, Texas, California, Louisiana
Catalysis	Michigan, Texas

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**REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED:** Southeastern United States

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## ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS

### BS/MS

**Process Engineering:** *Provides technical support in textile dyeing and finishing operations and in Specialty Chemicals production. Responsibilities include manufacturing compliance with customer product quality specifications and process efficiency/improvement project assignments.*

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# UNION CARBIDE CHEMICALS AND PLASTICS COMPANY INC.

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**Section M4556**

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**CITIZENSHIP REQUIREMENTS:** U.S. citizens and individuals legally authorized for full-time employment without restrictions.

**REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED:** Gulf coast, northeast, midwest, southeast, southwest, and Rocky Mountain

**HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW:** Send resume and photocopy of transcript(s) to above address. Be sure to include a cover letter specifying your functional and location preference. (See below)

## ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS

### BS/MS

Functional Area	Degree Level	Major Hiring Locations
Design (Process; Control Systems)	BS,MS	Charleston, WV
Environmental/Safety Engineering	MS	Charleston, WV
Manufacturing (Production; Env. Protection) and Process/Project Engineering	BS,MS	Bound Brook, NJ; New Orleans, LA; Houston and Victoria, TX; Charleston and Parkersburg, WV
Purchasing and Distribution	BS	Charleston, WV; Houston, TX
R&D (Polymer Applications/Tech Service; Process Development)	MS	Bound Brook, NJ; Charleston, WV; Tarrytown, NY
Technical Sales	BS	Metropolitan areas, nationwide

### PhD

Fields of Special Interest	Tech Center Locations
Catalysis, Polymers, Separations	Bound Brook, NJ; Charleston, WV

## ADDITIONAL INFORMATION

UCC&P has been recognized for its innovative technologies by receiving several prestigious Kirkpatrick Awards (sponsored by *Chemical Engineering Magazine*). Two of these, UNIPOL (polyolefins) and Low Pressure Oxo (alcohols), are licensed internationally and produce in excess of 15 billion lbs/yr of plastics and solvents.

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**HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW:** Please submit resume or application which clearly states educational background, objective, and work experience to:

Theresa Marinelli, Manager, College Relations  
Merck & Co., Inc.  
P.O. Box 2000  
Rahway, NJ 07065

## ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS

### BS/MS

<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
Corporate Division	BS/MS	Rahway, NJ; Somerset, NJ
Merck Sharp & Dohme Research Labs	BS/MS	Rahway, NJ; West Point, PA
Merck Chemical Manufacturing Division	BS/MS	Rahway, NJ; Albany, GA; Danville, PA; Elkton, VA
KELCO Division	BS/MS	San Diego, CA; Okmulgee, OK
Calgon Water Management Division	BS/MS	Pittsburgh, PA
Merck Pharmaceutical Manufacturing Division	BS/MS	West Point, PA

### PhD

<u>Fields of Special Interest</u>	<u>Tech Center Locations</u>
• Process changes which address the environmental aspects of plant operations	Merck Chemical Manufacturing Division Rahway, NJ; Albany, GA; Elkton, VA; Danville, PA
• Process development—from conception through to scale-up and eventual plant start up	Merck Sharp & Dohme Research Labs Rahway, NJ; West Point, PA
• Support the current technology and contribute toward development of new technology	Merck Pharmaceutical Manufacturing Division West Point, PA

## ADDITIONAL INFORMATION

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In each division we have highly skilled chemical engineers and we will continue to hire highly qualified applicants in the chemical engineering field.



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Winton Hill Technical Center  
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P&G, founded in 1837, having over \$24 billion in sales, is the largest consumer goods company in the United States. Of P&G's eighty thousand employees, over 3000 are graduate scientists and engineers (including more than 1000 with PhDs), doing research and development in 32 R&D facilities in 19 countries, supported by over \$700 million annual R&D spending. About half of our BS/MS entry-level hires are chemical engineers.

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## ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS

### BS/MS

Functional Area	Degree Level	Major Hiring Locations
Process Development	BS/MS	Cincinnati, OH; Memphis, TN; Norwich, NY; Shelton, CT
Product Development	BS/MS	See above locations
Products Research	BS/MS	See above locations
Packaging Development	BS/MS	See above locations

### PhD

Process Development	PhD	Cincinnati, OH; Norwich, NY; Shelton, CT
Product Development	PhD	See above locations
Applied Research	PhD	See above locations

## ADDITIONAL INFORMATION

P&G's leadership roles have been recognized externally in comparisons published by, for example, *Fortune*, *Forbes*, *Computerworld*, *Black Enterprise*, and *Savvy*. Internally, five of the twelve Charter Members of the Victor Mills Society, honoring excellence in technology at P&G, are chemical engineers.

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# DETERMINING THE KINETIC PARAMETERS CHARACTERISTIC OF MICROALGAL GROWTH

MARTINEZ SANCHO, M<sup>A</sup>E.,  
BRAVO RODRIGUEZ, V.,  
SANCHEZ VILLASCLARAS, S.,  
MOLINA GRIMA, E.  
*Universidad de Granada  
Jaen, Spain*

Due to the importance of biotechnology in today's world, the subject "biochemical engineering" has now been introduced into almost all syllabi for chemical engineering studies. It is therefore a worthwhile endeavor to increase the number of practical sessions pertinent to this discipline in chemical engineering laboratories.

Of particular interest in the study of the kinetics of microorganism growth is the situation where a nutrient, administered to the culture medium at a constant rate, limits growth. This may occur when restrictions are imposed by nutrient gases or by the light energy source in the case of photosynthetic cultures. In the former case, the transfer rate of the nutrient must be taken into consideration and in the latter the reduction of light intensity in the culture must be considered.

The basic aim of this practical session is to en-

able students to study experimentally the kinetics of growth in the unicellular algae *Chlorella pyrenoidosa* cultures under light-restricted conditions.

## BASES

When unicellular algae grow under low light intensities, a linear relationship is observed between the specific growth rate,  $\mu$ , and the light intensity,  $I$ . At high values of light intensity the specific rate, however, becomes constant. The most usual kinetic models for reproducing this variability are

*Hyberbolic Model* by Tamiya *et al.*<sup>[1]</sup>

$$\mu = \frac{\alpha \mu_m I}{\mu_m + \alpha I} \quad (1)$$

*Exponential Model*

$$\mu = \mu_m [1 - \exp(-I / I_s)] \quad (2)$$

The high extinction coefficients of microalgae in suspension determine a considerable reduction in light intensity according to the depth of the growth chamber. Moreover, if the cultures are developed

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**Vicente Bravo** is professor of chemical engineering at the University of Granada, where he has been since 1974. His research interests are in the areas of ethanolic fermentation, enzyme technology, and flue-gas desulfurization.



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**By following the variation in the biomass concentration with time in an autotrophic culture of *Chlorella pyrenoidosa* with no limitations imposed by nutrients or CO<sub>2</sub>, we ask that students obtain a growth curve for the algae, identify the exponential and linear growth phases, and calculate the parameters which characterize both phases.**

discontinuously using artificial light, even though the incident light intensity is constant, then the intensity within the suspension varies according to position and time.

Since the specific growth rate is an average value for the whole culture, the spatial variation of the light intensity determines that the relationship between the average growth rate and the distribution of the light may be expressed as follows<sup>[2]</sup>

$$\bar{\mu} = \frac{\int \int \int \frac{(I) \cdot dV}{V_c}}{\int \int \int \frac{I \cdot dV}{V_c}} \quad (3)$$

or

$$\bar{\mu} = \mu(I_m) \quad (4)$$

where

$$I_m = \frac{\int \int \int \frac{I \cdot dV}{V_c}}{\int \int \int \frac{I \cdot dV}{V_c}} \quad (5)$$

depending on the adaptation rate of the cells to the changing light intensities and the degree of mixing within the culture medium.

## EXPERIMENTS

By following the variation in the biomass concentration with time in an autotrophic culture of *Chlorella pyrenoidosa* with no limitations imposed by nutrients or CO<sub>2</sub>, we ask that students obtain a growth curve for the algae, identify the exponential and linear growth phases, and calculate the parameters which characterize both phases.

The overall interpretation of the results obtained by the students, using different incident light intensities, allows each of the two distinct kinetic models to be distinguished and their parameters to be obtained.

The integration of the kinetic model based on the two extreme situations possible for the distribution of light (Eq. 3 or 4) and its comparison with experimental results, concentration-time, would allow a quantitative difference to be established between the two situations.

## MATERIALS REQUIRED

The cultures are developed with equipment as shown in Figure 1.<sup>[3]</sup> Air is pumped in by a compressor (1), through a hydrophobic cotton filter (2), a stabilizing column (3) and a flow gauge, and passes into

the tank (5) where the air is humidified and mixed with CO<sub>2</sub> from the bottle (6).

By means of a gas distributor (8), the gaseous mixture (which is prepared in 5% CO<sub>2</sub> [v/v]) bubbles in the culture medium in the growth vessels. Filters by valves (13) are inserted into the three branches of the distributor.

The culture vessels (9), placed on magnetic stirrers (14), are three cylindrical containers with a capacity of one litre, covered by a jacket for the circulation of thermostatically-controlled water (10,11,12). These vessels have a glass top with two openings, one in the center for the bubbler and the other on one side for the loading of the culture (which

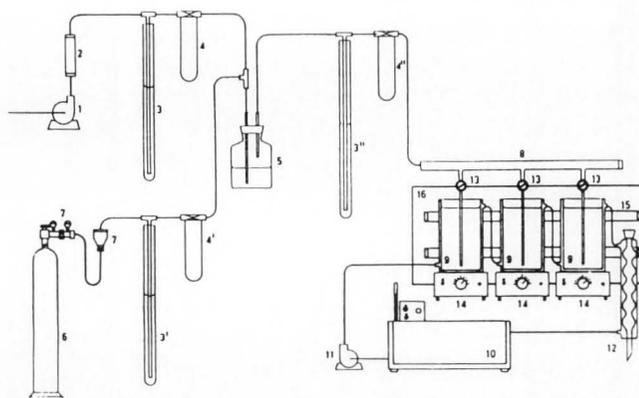


FIGURE 1. Experimental installation.

TABLE 1

Microorganism: *Chlorella pyrenoidosa*<sup>1</sup>  
 Culture medium: A pH: 6.5 Temperature: 30°C  
 Air-CO<sub>2</sub>: 0.5 v/v/min (5% CO<sub>2</sub> v/v)  
 I<sub>0</sub>: 740 lux

t, h	C, g·L <sup>-1</sup>	t, h	C, g·L <sup>-1</sup>
0.00	0.0078	79.25	0.2246
7.75	0.0122	94.25	0.3103
22.25	0.0253	103.25	0.3593
31.25	0.0359	118.75	0.4606
48.25	0.0833	127.75	0.5031
55.25	0.1123	151.75	0.6272
70.25	0.1804	166.25	0.7432

<sup>1</sup> Data obtained<sup>[3]</sup> with *Chlorella pyrenoidosa*, Chick 8H Emerson, from the collection held at the School of Botany in Cambridge which was provided by the Maime Ferrán Institute of the Science Research Council. The culture medium used is medium A, as proposed by Rodríguez-López.<sup>[4]</sup>

must be previously sterilized by filtration with 0.2  $\mu\text{m}$  nitrate cellulose filters), for the measurement and control of pH, and for the collection of samples. The equipment is sterilized in an autoclave before carrying out the experiment.

Two Westinghouse PLANT-GRO fluorescent light tubes (Mod. F. 40 w) (15), placed on a mobile panel (16), provide the light. The light intensity, measured with a luxometer, may be varied by altering the

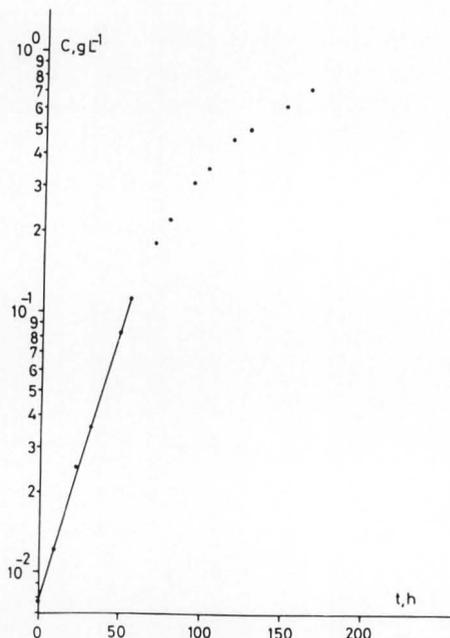


FIGURE 2. Variation of biomass concentration vs. time (semilogarithmic coordinates).

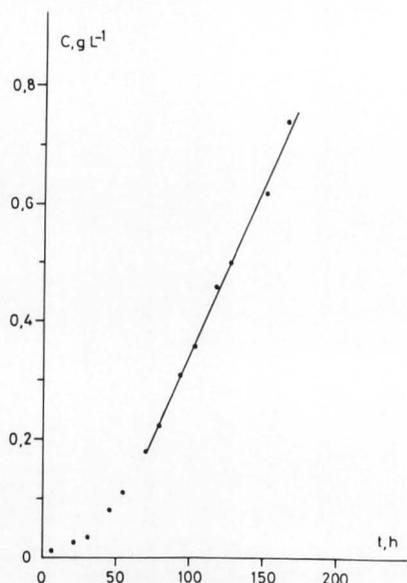


FIGURE 3. Variation of biomass concentration vs. time (linear coordinates).

distance between the lamps and the growth vessels, or by introducing black metal meshes with different apertures.

## PROCEDURE AND EXPERIMENTAL CONDITIONS

1. Preculture of the cells in a mineral medium solidified with 2% agar for four days before performing the practical session, under continuous lighting and at room temperature.
2. Sterilize the material.
3. Place the culture vessels in the equipment and adjust the light intensity desired within the range 200-2000 lux.
4. Prepare the culture medium, adjust the pH to 6.5, sterilize and add 500 cc to each of the culture vessels.
5. Adjust the temperature to 30°C.
6. Resuspend the preculture cells. Measure the concentration and calculate the volume to be inoculated so that each experiment is performed with an initial concentration of 0.008 gL<sup>-1</sup> expressed in dry weight. Inoculate.
7. Adjust the composition and flow rate of the gaseous mixture added in the proportion of 0.5 v/v/min.
8. Collect samples throughout the experiments.

## ANALYTICAL TECHNIQUE

The cellular concentration (g dry biomass)·L<sup>-1</sup> is determined indirectly after suitable dilution through the absorbance of the cell suspension measured at 600 nm. To convert absorbance to concentration, the calibration line valid up to A<sub>600</sub> < 0.5 is used,

$$C(\text{gL}^{-1}) = 0.49 A_{600} \quad r^2 = 0.999 \quad (6)$$

which has been obtained by measuring the absorbances of the suspensions of determined concentration after centrifugation, washing, and dessication at 105°C until a constant weight is achieved.

This correlation has previously been obtained with the microorganism and the culture medium specified in Table 1, and is valid for the experimental conditions to be used in the practical session.

## RESULTS AND DISCUSSION

### Interpretation of Individual Results

As an example, the biomass concentration at different culture times is shown in Table 1 in an experiment performed under the conditions indicated. The representation of the experimental data in semi-logarithmic and linear coordinates (Figures 2 and 3) demonstrates graphically the exponential growth phase (the straight line in Figure 2) and the linear growth phase (the straight line in Figure 3).

By integrating the biomass balance during the exponential growth phase, in which  $\mu$  is constant and with the initial condition that at  $t = 0$ ,  $C = C_0$  (as no appreciable lag phase is observed, then the following is obtained:

$$\ln(C / C_0) = \mu_{\max} \cdot t \quad (7)$$

From the slope of this line, the maximum specific growth rate in  $h^{-1}$  may be calculated.

The integration of the biomass balance during the linear growth phase, in which

$$\mu \cdot C = \text{constan } t = P \quad (8)$$

leads to

$$C = P \cdot t + b \quad (9)$$

where  $b$  represents an integration constant. This equation provides  $P$  in  $gL^{-1}h^{-1}$ .

### Overall Interpretation of the Results

The maximum specific growth rates during the exponential phase and the growth rates during the linear phase in experiments performed at seven different incident light intensities are recorded in Table 2. The graph representing these parameters in linear coordinates vs. the incident light intensity shows the experimental variation obtained (Figures 4 and 5).

The specific rate during the exponential growth phase seems to vary linearly with  $I_0$  up to approximately 1000 lux, and a saturation effect is observed thereafter.

The adjustment of pairs of values  $\mu_{\max} - I_0$  to the kinetic models is carried out through the least squares method to the linearized form of the hyperbolic model by Tamiya,

$$\frac{1}{\mu_{\max}} = \frac{1}{\mu_m} + \frac{1}{\alpha I_0} \quad (10)$$

and through non-linear regression to the exponen-

tial model (Eq. 2).

The model which best reproduces the experimental variation may be selected by using the minimum from the accumulative sum of the squares of the residues as a criteria. For data collected in Table 2, the exponential model provides the optimum adjustment when the following values are used for the parameters

$$\mu_m = 0.099 h^{-1} \quad \text{and} \quad I_s = 926 \text{ lux}$$

The linear variation  $P - I_0$  confirms the light limitation in the linear growth phase. The adjustment of these values allows the prediction of growth rate during this phase for any value of incident light

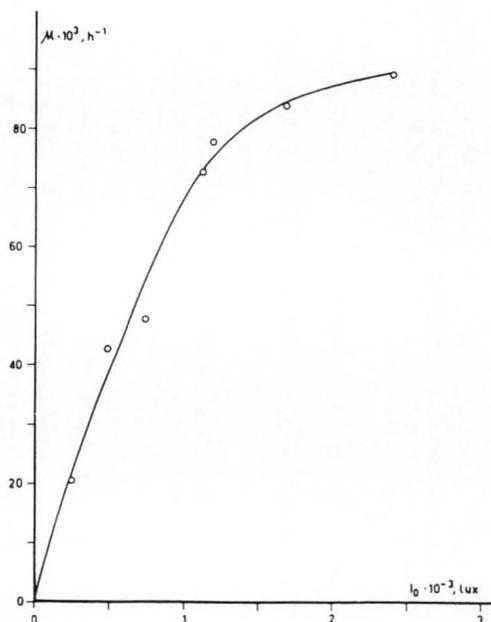


FIGURE 4 Variation of specific growth rate vs. light intensity.

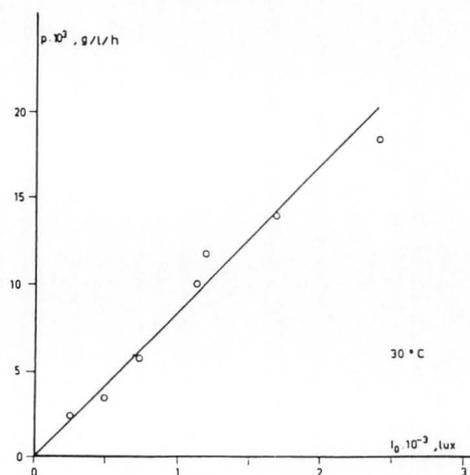


FIGURE 5. Variation of growth rate during linear phase vs. light intensity

TABLE 2<sup>1</sup>

Microorganism: *Chlorella pyrenoidosa*  
 Culture medium: A pH: 6.5 Temperature: 30°C  
 Air-CO<sub>2</sub>: 0.5 v/v/min (5% CO<sub>2</sub> v/v)

$I_0, \text{lux}$	$\mu_{\max}, h^{-1}$	$P, g \cdot L^{-1} \cdot h^{-1}$
252	0.0205	0.00241
494	0.0427	0.00348
740	0.0478	0.00577
1128	0.0727	0.0101
1194	0.0777	0.0118
1688	0.0837	0.0139
2410	0.0891	0.0184

<sup>1</sup> Data from [3].

intensity. In this case the relationship is

$$P = 8.45 \cdot 10^{-6} I_0 \quad (11)$$

For integration of the most appropriate kinetic model, in respect of the extreme situations for light distribution, the point-by-point variation of the light intensity in the culture vessel must be known *a priori*. The difficulty in establishing this variation in a cylindrical vessel illuminated from the front leads to the need for an analogy with a parallelepipedic vessel<sup>[5]</sup> in which the point-by-point ( $I[x]$ ) and average ( $I_m$ ) light intensities may be calculated by means of

$$I(x) = I_0 \exp(-k_a Cx) \quad (12)$$

$$I_m = \frac{I_0}{k_a LC} [1 - \exp(-k_a LC)] \quad (13)$$

where  $k_a$  is the extinction coefficient with a value of  $2.42 \text{ Lg}^{-1}\text{cm}^{-1}$ , and  $L$  is the equivalent length of the culture chamber in centimeters.

Inclusion of Eq. (12) into Eq. (2) provides the solution to the integral of Eq. (3), and results in

$$\begin{aligned} \bar{\mu} = & \frac{I_0 \mu_m}{I_s k_a LC} [1 - \exp(-k_a LC)] \\ & - \frac{I_0^2 \mu_m}{I_s^2 4 k_a LC} [1 - \exp(-2k_a LC)] \\ & + \frac{I_0^3 \mu_m}{I_s^3 18 k_a LC} [1 - \exp(-3k_a LC)] + \dots \quad (14) \end{aligned}$$

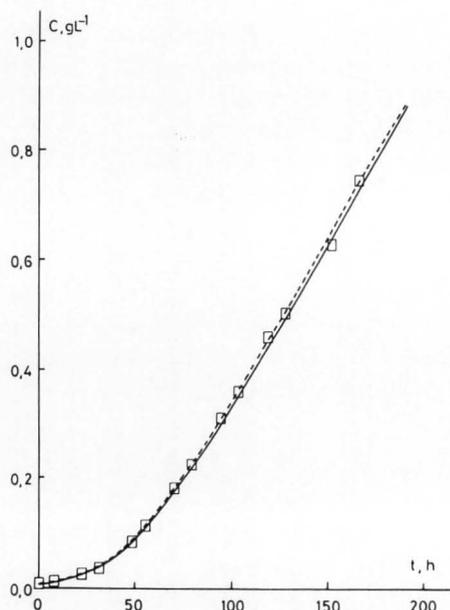


FIGURE 6. Variation of biomass concentration vs. time (= experimental values; - - - Eq. (3),  $L = 4.5 \text{ cm}$ ; — Eq. (4),  $L = 5 \text{ cm}$ ).

which provides the average specific growth rate as a function of the concentration when cell growth adapts to the point-by-point light intensity which the microalgae receive.

Furthermore, inclusion of Eq. (13) into Eq. (2) leads to

$$\bar{\mu} = \mu_m \left\{ 1 - \exp\left(-I_0 [1 - \exp(-k_a LC)]\right) / (k_a LC I_s) \right\} \quad (15)$$

which allows the calculation of the average specific growth rate when the cells adapt to an average value of light intensity.

In both situations, the numerical integration of the biomass balance

$$\frac{1}{C} \frac{dC}{dt} = \bar{\mu} \quad (16)$$

through Eqs. (14) or (15) will allow the prediction of the variation in biomass concentration in time. This calculation has been carried out for both situations, modifying the value of the equivalent length until a satisfactory reproduction of the experimental results is obtained. Figure 6 shows this adjustment with a value of  $L = 4.5 \text{ cm}$ , for the situation described by Eq. (3) and for the situation corresponding to Eq. (4) with a value of  $L = 5 \text{ cm}$ .

The almost negligible difference between both values for  $L$  clearly shows the difficulty involved in distinguishing between the two situations. In a previous study,<sup>[6]</sup> however, using a different procedure, the value of  $L$  was found to range from  $5.1$  to  $7.1 \text{ cm}$ , which would seem to indicate that cellular growth adapts to average light intensities. This adaptation was proved in another study by altering the stirring rates.<sup>[5]</sup>

## REFERENCES

1. Tamiya, H., E. Hase, K. Shibata, A. Mituya, T. Iwamura, T. Nihei, and T. Sasa, "Kinetics of Growth of *Chlorella*, with Special Reference to its Dependence on Quantity of Available Light and on Temperature," in *Agal Culture from Laboratory to Pilot Plant*, J.S. Burlew, Carnegie Inst. Publ. 600, p. 204 (1953)
2. Fredrickson, A.G., and H.M. Tsuchiya, "Microbial Kinetics and Dynamics," in *Chemical Reactor Theory: A Review*, S. Lapidus, N.R., Amundson, Prentice-Hall, p. 405 (1977)
3. Camacho Rubio, F., and Martínez Sancho, M<sup>a</sup>E., *An. Quim.*, **79**, p. 265 (1983)
4. Rodríguez López, M., *Nature*, **203**, p. 666 (1964)
5. Camacho Rubio, F., Padiál Vico, A., and Martínez Sancho, M<sup>a</sup>E., *An. Quim.*, **78**, p. 371 (1982)
6. Martínez Sancho, M<sup>a</sup>E., "Influencia de la Intensidad de Iluminación en el Crecimiento de *Chlorella pyrenoidosa*," PhD Thesis, Granada University (1980) □

# CHEMICAL REACTION ENGINEERING APPLICATIONS IN NON-TRADITIONAL TECHNOLOGIES

## *A Textbook Supplement*

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Recent years have witnessed an expansion of chemical engineering activity in areas such as materials processing (e.g., microelectronics, superconductors, composites) and biotechnology. This expansion has been accompanied by a reduction in chemical engineering opportunities in the more traditional areas of petroleum processing and commodity chemicals.

These events have led to much introspection in the chemical engineering community. One effect on education has been a new and widely-recognized need to broaden the technological base of undergraduate education. Students must be exposed to chemical engineering applications in the frontier areas in addition to continued exposure to applications in traditional petroleum processing and petrochemical applications.

One approach to providing the necessary exposure is to develop elective courses dealing with specific technologies (e.g., biochemical technology, microelectronics processing, polymer processing). A sec-

ond approach is to incorporate examples dealing with non-traditional technologies in each of the core undergraduate courses. This second approach has the advantage of more easily integrating the new technologies with fundamental principles and obviating the need to find additional room in an already crowded curriculum.

A barrier to weaving examples from new technologies into existing courses, however, is that most chemical engineering textbooks, though good at presenting fundamental principles, generally do not provide examples and applications from non-traditional technologies. Thus, the instructor is forced to identify and develop such examples on his own. In some cases the problem has been recognized and steps have been taken to provide instructors with useful materials. A good example is the book *Chemical Engineering Education in a Changing Environment*<sup>11</sup> which provides the proceedings of a conference sponsored jointly by the Engineering Foundation, the National Science Foundation, and the American Institute of Chemical Engineers. It presents a large number of problems that deal with non-traditional technologies, along with their solutions. The problems are intended for use as examples in lectures or as homework assignments. Another example is a set of articles on microelectronics processing that recently appeared in *Chemical Engineering Education*.<sup>12-61</sup>

This paper describes a set of educational materials that we have developed which deal with chemical engineering applications in "emerging" technologies. These materials take the form of a textbook supplement. Our goal was to develop materials for use in a chemical reaction engineering course. Thus, we selected examples from microelectronics processing and

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***A barrier to weaving examples from new technologies into existing courses... is that most chemical engineering textbooks, though good at presenting fundamental principles, generally do not provide examples and applications from non-traditional technologies. Thus, the instructor is forced to identify and develop such examples on his own.***

biochemical technology that illustrate key concepts in kinetics and reaction engineering. Here we will describe the organization and content of our textbook supplement and show how it can be integrated into an undergraduate reaction engineering course. A copy of the supplement can be obtained by writing to the authors.

### **MOTIVATION FOR DEVELOPING THE COURSEPACK**

We began developing the materials described in this paper in the spring of 1988. At that time there were very few such educational materials available to the chemical engineering community even though it was quite clear that examples from microelectronics processing (for instance) could easily be used to illustrate key reaction engineering principles. Unfortunately, existing textbooks provided very few applications of reaction engineering principles to problems encountered in microelectronics processing and biotechnology.

Table 1 lists several reaction engineering texts and the number of pages each devotes to these two particular technologies. As can be seen, many of the texts completely omit any reaction engineering applications in these technologies. Hill and Fogler, however, include several pages on enzyme kinetics. Nauman likewise covers Michaelis-Menten kinetics, and he also includes a few pages on fermentation.

Reaction engineering applications in microelectronics processing are much more scarce, however.

Nauman gives a brief and largely qualitative discussion of reaction engineering issues in the fabrication of electronic devices. Fogler provides a few problems dealing with chemical vapor deposition at the end of his chapter on heterogeneous reactions, along with three problems (without solutions) concerning microelectronics fabrication in an appendix.

An encouraging trend, evident in the table, is that the most recent books have the most material relevant to biotechnology and microelectronics processing. This trend will certainly continue as new and revised textbooks are published. Fogler's second edition, for instance, has an expanded treatment of these topics.

Our desire to integrate examples from non-traditional technologies into the traditional chemical reaction engineering course and the omission of such examples in most texts motivated our work in developing a textbook supplement. This supplement took the form of a spiral-bound coursepack that the students could purchase for a nominal fee from a local copying center.

### **OVERVIEW AND ORGANIZATION OF THE COURSEPACK**

The coursepack comprises two main sections. One deals with microelectronics processing and the other with biochemical technology. The microelectronics processing section contains three chapters, and the topics covered are chemical vapor deposition, plasma etching, and the thermal oxidation of silicon. The biochemical technology section contains two chapters: one concerns fermentation and bioreactor design and the second discusses catalysis by immobilized enzymes.

Each of the chapters comprises three sections: Introduction, Applications of Chemical Reaction Engineering, and Problems. The first section introduces one particular aspect of an emerging technology and provides background material necessary for the subsequent sections. The second section illustrates, via examples, how established reaction engineering principles can be applied to this particular aspect of the technology. Detailed derivations are often omitted, and the student is expected to refer to

**TABLE 1**  
**Textbooks and Non-Traditional Technologies**

Author	Pages Devoted to	
	Biotechnology	Microelectronics
Carberry (1976) <sup>[7]</sup>	0	0
Hill (1977) <sup>[8]</sup>	7	0
Holland and Anthony (1979) <sup>[9]</sup>	0	0
Butt (1980) <sup>[10]</sup>	0	0
Smith (1981) <sup>[11]</sup>	0	0
Fogler (1986) <sup>[12]</sup>	8	3
Nauman (1987) <sup>[13]</sup>	11	3
Froment and Bischoff (1990) <sup>[14]</sup>	0	0

the textbook for basic explanations of the principles. The final section provides several problems that allow the students to use what they have learned in the earlier sections.

We have designed this textbook supplement so that it can be easily integrated into a chemical reaction engineering class. The coursepack is structured so that the chemical reaction engineering principles that are being employed are clearly evident within the applications section of each chapter. Table 2 summarizes the general reaction engineering principles emphasized in each chapter in the coursepack.

Organizing the coursepack around reaction engineering principles facilitates the integration of relevant examples from non-traditional technologies into the traditional course. For example, the concepts involved in the design of an isothermal CSTR can be illustrated using a rate law for cell growth kinetics as well as one for a generic reaction such as  $A \rightarrow B + C$ . Additionally, the key ideas behind the derivation of rate laws for heterogeneous catalytic reactions (*i.e.*, Langmuir-Hinshelwood-Hougen-Watson kinetics) can also be applied to derive rate expressions for chemical vapor deposition processes. As a final example, transport and reaction in the inter-wafer region of a horizontal plasma etching reactor is amendable to the same type of analysis employed in modeling diffusion and reaction in a catalyst particle.

To illustrate more fully the manner in which the coursepack can be integrated into the reaction engineering class, consider the chapter on chemical vapor deposition which features four different applications of chemical kinetics and reaction engineering: collisional activation of gas-phase reactions, heterogeneous reaction kinetics, diffusion and reaction, and chemical equilibrium.

The illustration of the first principle uses the reaction  $\text{SiH}_4 \rightarrow \text{SiH}_2 + \text{H}_2$ , which can occur in the gas phase during the CVD of polycrystalline silicon from silane. Here we employ the simple Lindemann mechanism for unimolecular reactions and the pseudo-steady-state approximation to derive a rate law for the reaction. The rate equation clearly shows that the reaction can be second order in silane at low pressures and first order at high pressures. This example can be used in the reaction engineering course to reinforce the concepts of elementary reaction steps, active centers, and the steady-state approximation.

The second application in the CVD chapter deals

with heterogeneous reaction kinetics. In this section we use the standard Langmuir-Hinshelwood-Hougen-Watson formalism to derive a rate law for deposition of polycrystalline silicon from silane. This example illustrates the application of elementary reactions (adsorption, desorption, surface reaction) and the concept of a rate-limiting step.

The third application in the CVD chapter involves an analysis of reaction and diffusion in a horizontal, multiple-wafer-in-tube, low-pressure CVD reactor. The reactor contains a large number of closely spaced wafers upon which it is desired to deposit a thin, uniform film. The direction of flow of the gaseous reactants is normal to the wafer surface so diffusion is the dominant mode of transport between the wafers. Mathematically, this problem is identical to that of reaction and diffusion in a porous, cylindrical catalyst particle. Thus, the principles of coupled rate processes (*i.e.*, diffusion and surface reaction) can be applied in this case, and the Thiele modulus and the concept of an effectiveness factor emerge quite naturally.

The final application in the CVD chapter deals with chemical equilibrium for the reaction  $\text{SiH}_4 \leftrightarrow \text{Si}_{(s)} + 2\text{H}_2$ . Here, we calculate the equilibrium constant for the reaction and then use it to show that the reactor pressure and temperature and the feed stream composition determine the direction in which the reaction occurs. That is, some operating conditions can lead to etching (*i.e.*, removal of silicon from the surface) whereas other conditions can lead to deposition of Si. This example illustrates the importance of thermodynamics in chemical reaction engineering.

One of the pedagogical benefits of using examples from non-traditional technologies alongside their more traditional counterparts is that doing so helps to emphasize the importance of the underlying physical and chemical phenomena rather than the spe-

**TABLE 2**  
Reaction Engineering Principles in Coursepack

Principles	Chapter				
	CVD	Plasma Etching	Silicon Oxidation	Fermentation	Enzyme Catalysis
Reactor Modeling	✓	✓		✓	✓
Chemical Equilibrium	✓				
Reaction Kinetics	✓			✓	✓
Diffusion and Reaction	✓	✓	✓		✓

cific example that is being used to illustrate the phenomena. For instance, when students begin to realize that the same set of principles can be used to understand the behavior of a fixed-bed catalytic reactor and the behavior of a low-pressure, chemical vapor deposition reactor, then they are beginning to focus on those fundamental principles rather than on the specific technological applications. As a result, the students obtain a deeper appreciation for the general applicability of chemical engineering science.

## SUMMARY

We have developed a textbook supplement that facilitates the integration of examples from non-traditional technologies into a reaction engineering course. These educational materials provide a means for introducing students to the application of chemical reaction engineering principles in microelectronics and biochemical technology. The coursepack has been used in classes at The University of Michigan, and the student evaluations have been generally favorable.

## ACKNOWLEDGEMENT

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## REFERENCES

1. Sandler, S.I., and B.A. Finlayson, eds, *Chemical Engineering Education in a Changing Environment*, Engineering Foundation, New York, NY (1988)
2. Anderson, T.J., *Chem. Eng. Ed.*, **24**, 26 (1990)
3. Hess, D.W., *Chem. Eng. Ed.*, **24**, 34 (1990)
4. McConica, C.M., *Chem. Eng. Ed.*, **24**, 38 (1990)
5. Takoudis, C.G., *Chem. Eng. Ed.*, **24**, 42 (1990)
6. Orazem, M.E., *Chem. Eng. Ed.*, **24**, 48, (1990)
7. Carberry, J.J., *Chemical and Catalytic Reaction Engineering*, McGraw-Hill Book Company, New York, NY (1976)
8. Hill, C.G., *An Introduction to Chemical Engineering Kinetics and Reactor Design*, John Wiley & Sons, Somerset, NJ (1977)
9. Holland, C.D., and R.G. Anthony, *Fundamentals of Chemical Reaction Engineering*, Prentice-Hall, Englewood Cliffs, NJ (1979)
10. Butt, J.B., *Reaction Kinetics and Reactor Design*, Prentice-Hall, Englewood Cliffs, NJ (1980)
11. Smith, J.M., *Chemical Engineering Kinetics*, McGraw-Hill Book Company, New York, NY (1981)
12. Fogler, H.S., *Elements of Chemical Reaction Engineering*, Prentice Hall, Englewood Cliffs, NJ (1986)
13. Nauman, E.B., *Chemical Reactor Design*, John Wiley and Sons, Somerset, NJ (1987)
14. Froment, G.F., and K.B. Bischoff, *Chemical Reactor Analysis and Design*, John Wiley and Sons, Somerset, NJ (1990)

□

## REVIEW: Numerical Methods

*Continued from page 144*

until a steady state is reached. Another interesting feature of the book is its excellent compilation of problems.

The reviewer has serious doubts whether a student can truly appreciate the chemical engineering orientation of the book at the sophomore level—one can easily get weighted down by new concepts which can divert the attention away from the numerical techniques themselves. It would be better to use this text at the senior level, after a student has been exposed to the basic courses in chemical engineering. But at that level, one could possibly introduce the orthogonal collocation method, which is quite popular now but which does not find a place in this text. Also, one could then do more justice to the stiffness of ODE's (although some introductory discussion exists on stability criteria for IVP's) and to finite element techniques.

Overall, this book will satisfy the demands of undergraduate chemical engineering students who usually have difficulty in understanding the presentations in more general texts. With some additional material incorporated by an instructor, it could be an excellent text at the senior level. Some instructors can possibly use this as a text at earlier stages in the curriculum. □

## ChE books received

*Computational Quantum Chemistry*, by Alan Hinchliffe; John Wiley & Sons, 1 Wiley Dr., Somerset, NJ 08875-1272; 112 pages, \$34.95 (1988)

*Diffusion and Convection in Porous Catalysts*, Webster and Strieder, eds; AIChE, 345 East 47th St., New York, NY 10017; 96 pages; \$20 members, \$35 Others (1988)

*Separation Technology*, Li and Strathmann, eds; AIChE, 345 East 47th St., New York, NY 10017; 633 pages; \$50 Members, \$70 Others (1988)

*Environmental Management Handbook: Toxic Chemical Materials and Wastes*, by Kokoszka and Flood; Marcel Dekker, Inc., 270 Madison Ave., New York NY 10016; 656 pages, \$125 (1989)

*Fatty Acids in Industry: Processes, Properties, Derivatives, Applications*, edited by Johnson and Fritz; Marcel Dekker, Inc., 270 Madison Ave., New York, NY 10016; 688 pages, \$150 (1989)

*Droll Science*, compiled by Robert L. Weber; The Humana Press Inc., PO Box 2148, Clifton, NJ 07015; 352 pages, \$22.50 (1987)

*How to Write and Publish a Scientific Paper*, 3rd edition, by Robert A. Day; Oryx Press 2214 North Central at Encanto, Phoenix, AZ 85004; 224 pages, \$21.95 (1988)

*The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and which elucidate difficult concepts. Please submit them to Professors James O. Wilkes and Mark A. Burns, Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.*

## A SIMPLE HEAT OF CRYSTALLIZATION EXPERIMENT

NOEL DE NEVERS  
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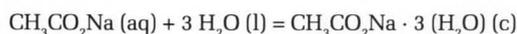
A permanent problem in engineering education is to find simple, portable, low-cost classroom demonstrations of the principles we present to our students. The more we can convince them that the equations in their textbooks describe what actually occurs in nature, the better engineers they are likely to become. For that reason, educators are always looking for opportunities to present experimental confirmation of textbook principles. If possible, we seek to find simple things, available to the public in general, which illustrate engineering principles—and then to show the students how those principles apply to things in their daily lives.

A sportsman's handwarmer is a great comfort on cold days. It is also a simple, portable tool that can be used to show students that textbooks do describe the real world. The "Heat Solution Reusable Heat Pack"<sup>[1]</sup> is available in sporting-goods stores for \$3.00. It is a 3-by-4 inch clear-plastic pouch, containing approximately 100 gm of an approximately 50 wt% solution of sodium acetate (NaAc) in water, plus a

roughly 5/8-inch diameter, thin, stainless steel disc.

This device can be used in a sophomore heat and material balances class by first assigning the following as a homework problem or exam question:

A solution of 50% by weight water and 50% by weight sodium acetate (NaAc), ( $\text{CH}_3\text{CO}_2\text{Na}$ , molecular weight 82), is at 25 °C. This solution now crystallizes adiabatically by the reaction



for which the heat effect is  $\Delta H = -30.74$  kJ/mol of NaAc.

Here assume that the original solution was one mole of NaAc (82 gm) and 82 gm of water. At equilibrium at the final temperature the composition is 56.44 gm of crystalline  $\text{CH}_3\text{CO}_2\text{Na} \cdot 3(\text{H}_2\text{O})$ , and a solution consisting of 59.59 gm of water and 47.97 gm of dissolved NaAc.

The heat capacities are: water,  $C_p = 4.18$  J/gm °C,  $\text{CH}_3\text{CO}_2\text{Na} \cdot 3(\text{H}_2\text{O})(\text{c})$ ,  $C_p = 2.4$  J/gm °C, and dissolved NaAc,  $C_p = 2.58$  J/gm °C.

What is the final temperature of the mixture of NaAc solution and crystals after equilibrium is reached?

### SOLUTION

For an adiabatic, constant-pressure batch process with no work other than expansion against the surroundings, we have

$$\Delta H = 0 = m_{\text{crystallized}} \Delta H_{\text{crystallization}} + \sum m C_p \Delta T$$

$$\Delta T = \frac{-m_{\text{crystallized}} \Delta H_{\text{crystallization}}}{\sum m C_p}$$

$$m_{\text{crystallized}} = \frac{56.44 \text{ gm of trihydrate}}{136 \frac{\text{gm}}{\text{mol of trihydrate}}} = 0.415 \text{ mols}$$



*Noel de Nevers has been a faculty member at the University of Utah since 1963. His principal technical interests are fluid mechanics, thermodynamics, and air pollution. He has also developed a course and edited a book of readings on Technology and Society. In addition to his technical work, he had three of his laws published in the 1982 Murphy's Laws compilation and won the coveted title of "Poet Laureate of Jell-O" at the annual Jell-O Salad Festival in Salt Lake City.*

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$$\Delta T = \frac{-0.415 \text{ mol} \cdot \left(-30,740 \frac{\text{J}}{\text{mol}}\right)}{\left(56.44 \text{ gm} \cdot 2.4 \frac{\text{J}}{\text{gm} \cdot \text{C}} + 59.59 \text{ gm} \cdot 4.18 \frac{\text{J}}{\text{gm} \cdot \text{C}} + 47.97 \text{ gm} \cdot 2.58 \frac{\text{J}}{\text{gm} \cdot \text{C}}\right)} = 25.1 \text{ }^{\circ}\text{C}$$

$$T_{\text{final}} = 25 + 25.1 = 50.1 \text{ }^{\circ}\text{C}$$

Thus one would expect the final temperature to be about 25°C higher than the initial temperature, for this initial temperature.

After the problem has been discussed in class, the instructor measures the temperature of the uncrystallized pouch; this is most easily accomplished by using a small portable LCD thermocouple gauge (Kiethley Model 870 Digital Thermometer or equivalent). The instructor (or a student) lays the pouch on a piece of any kind of insulating plastic foam with the thermocouple between the pouch and the plastic. The gauge quickly shows the temperature, which should be practically room temperature.

Then the instructor initiates crystallization by flexing the stainless steel disc inside the pouch, which presumably causes a small oxide particle to flake off, which in turn starts the crystallization. The entire crystallization takes place in three to five seconds, with a visible, white, opaque crystallization front moving across the pouch from the initiation point. The instructor (or the students) then measures the temperature as described above, finding that it does increase by very close to 25°C. The instructor then hands the pouch around to the students so they can feel that it is quite warm.

This is probably as much as the instructor would want to do with the demonstration and/or the calculations in a typical sophomore heat and material balances class. But there are even more possibilities for instruction in this simple device.

The instructor can use the experiment for demonstrating supersaturation and nucleation. The device can be regenerated and reused by placing it in boiling water for a few minutes and then allowing it to cool. The published melting point of the pure trihydrate is 58°C, so at room temperature it is about 35°C supercooled. It can be supercooled to freezer temperature (-13°C) without initiating solidification.

The homework or examination problem can be made more complex by not specifying the final masses of crystals, water, and dissolved NaAc, but rather by specifying the initial state and giving the final condition that the uncrystallized solution has 0.805 gm dissolved NaAc per gm of water (which corresponds

to equilibrium at 49°C) in the final state. In that case the student may solve for the values of the final masses shown in the problem by writing three material balances. If  $x$  represents the grams of crystalline trihydrate,  $y$  the grams of water, and  $z$  the grams of dissolved NaAc, then

$$x + y + z = 164 \text{ gm}$$

$$z = 0.805 y$$

$$y = (164 - 82) - x \cdot (54 \text{ gm water of hydration} / 136 \text{ gm trihydrate})$$

These may be solved together to find the values in the problem statement.

The problem can again be made more complex by using a heat capacity equation for the crystalline trihydrate instead of using the average values shown above. The data in reference (2) are reasonable well represented by

$$C_p = 1.44 \text{ J/gm }^{\circ}\text{C} + (0.028 \text{ J/gm }^{\circ}\text{C}^2) T$$

The average  $C_p$  value used in the problem corresponds to  $T = 34.3^{\circ}\text{C}$  in this formula, which is about half-way between room temperature and the final temperature of the crystallized system.

The final temperature of the hand warmer is surprisingly insensitive to the initial temperature because the solubility of sodium acetate in water increases rapidly in the range from about 45°C to the melting point of the trihydrate at 58°C.<sup>[3]</sup> Using the above equations and working backwards from assumed final temperatures, one computes that

Assumed Final Temperature, °C	NaAc Solubility gm/gm Water	Computed Starting Temperature °C
48	0.78	20.4
50	0.83	27.5
52	0.90	37.7

Thus, for initial temperatures between 20.4 and 37.7°C the computed final temperatures change only from 48 to 52°C. Experimentally, the independence of final temperature on starting temperature seems even stronger than this calculation suggests, but the experimental temperature measurements are not very precise. For an initial temperature of -13°C (freezer temperature) the observed  $\Delta T$  was 46°C, and the resulting crystalline mass at 33°C was quite firm. For an initial temperature of 41°C the final temperature was 51°C ( $\Delta T = 10^{\circ}\text{C}$ ) and the resulting crystalline mass was quite mushy.

The calculated results are quite sensitive to the assumed initial water content. Again, using the above assumptions we may calculate

Assumed Final Temperature, °C	Assumed Initial NaAc wt. Fraction in Solution	Computed Starting Temperature °C
50	0.49	32.8
50	0.50	27.5
50	0.51	22.1

In making up the problem, the value of 50 wt% NaAc was chosen because the resulting calculations gave the best match to the experimental tests. (By phone a Prism staff member said the concentration was between 50 and 55 wt%, but declined to say exactly what the value was.)

The heat of crystallization was computed from the data in reference 3.

## REFERENCES

1. Prism Technologies, 3111 N. Knox, Chicago, IL 60641 (312-685-0999)
2. *International Critical Tables*, E. W. Washburn, ed., Vol. 5, pg 100, McGraw-Hill, NY (1929)
3. *Gmelins Handbuch der anorganischen Chemie* 8. Auflage, System Nummer 21, Natrium, Verlag Chemie, GmbH, Berlin, pg. 822 (1928)
4. Rossini, F.D., et al., "Selected Values of Chemical Thermodynamic Properties," *NBS Circular 500*, pg. 470 (1952) □

## ChE book review

### PROCESS CONTROL: STRUCTURES AND APPLICATIONS

by Jens Balchen and Kenneth Mummé

Van Nostrand Reinhold, 115 Fifth Ave., New York, NY 10003; \$59.95 (1987)

Reviewed by

**Coleman B. Brosilow**

Case Western Reserve University

This book aims to "bridge the long-standing gap between process and control." Toward this end, the second chapter reviews most control theory and control system design methods. Chapter 3 gives a mainly qualitative description of many important chemical and physical processes, ranging in complexity from valves to crystallization and reaction processes. Chapters 4 and 5 present alternate control structures for the processes described in Chapter 3. These structures are combinations of PID, ratio, feedforward, and cascade controllers, along with arithmetic and logic blocks which are standard in most distrib-

uted control systems. The book concludes by presenting the control structures for several integrated process systems such as a paper machine and an ammonia plant. The discussion is mostly qualitative.

The authors have undertaken to present an immense amount of material to an extremely wide audience; indeed, too much material to too wide an audience. Chapter 2, by necessity, gives only the most cursory overview of the topics covered. In some places the need to be concise has led to inaccurate and/or misleading statements as, for example, on page thirteen where it is stated that in order for a feedback controller to be effective, the loop transfer function  $h_0(s)$  must satisfy  $|h_0(s)| \gg 1$ . The discussion on multivariable decoupling and predictive control completely omits treatment of control effort constraints. Such an omission is unforgivable in a text that claims to bridge gaps.

Later chapters suffer from very uneven coverage of subject matter. While most discussions describe various pieces of equipment and how they work, every so often the discussion gets very detailed. In the discussion of compressors, for example, it is pointed out that "it is important that the pressure and temperature be such that the gas does not reach the critical point." This somewhat imprecise statement is then illustrated by PVT diagrams (page 103) for water and carbon dioxide, with no explanation of how to use the diagrams. In the discussion of chemical reactors, the reader is presented with a partial differential equation model for the reaction  $A \rightarrow B$  in a plug flow tubular reactor (pages 238-239). These equations are then followed immediately by the statement that if the heat transfer coefficient can be used as a control variable, it can be expressed in terms of a new variable which is the relative change in heat transfer coefficient with respect to the steady-state heat transfer coefficient. No justification is given for the equation which follows nor is it clear why the change of variable was even mentioned since the subject is immediately dropped. This reviewer remains confused as to why we would even wish to use variations in heat transfer coefficient as a control variable for tubular reactors.

In summary, it is difficult to know to whom to recommend this book. It assumes too much chemical engineering background for the average control engineer and too much control background for the average chemical engineer. Perhaps, my academic colleagues will find useful some of the detailed process descriptions and P&I diagrams. □

## DEPARTMENT: U Mass

*Continued from page 125.*

microstructure and morphology in both flow systems and porous materials. Winter studies structural development in well-defined flows of different classes of polymeric systems, such as phase-separating block copolymers and liquid crystalline polymers. Self-similar molecular structure is exhibited by cross-linking polymers at the sol-gel transition. Malone studies the effect of flows on the morphology and phase behavior of binary polymer blends. Computer image analysis is used for characterization and control of the process. Ng has shown by both simulation and CAT-scan analysis that the liquid distribution during flow through a bed of packing is a manifestation of local flow features involving several particles. Because of his research activities in the transport and reaction areas, his work in process design has a strong focus on the underlying physics.

The morphology of amorphous and crystalline oxides is a focus of several projects. Dynamic adsorption-desorption of liquid nitrogen or krypton, mercury porosimetry and electron microscopy are three tools used to characterize morphology. Conner and Laurence study the effects of pore size and porosity of silica-supported catalysts on the fragmentation and yield during the initial stages of olefin polymerization. In a similar vein, Conner has been collaborating with scientists at Brookhaven National Laboratories to pioneer the development of X-ray synchrotron computed microtomography and its application to characterize the morphology of olefin polymerization catalysts. Minimization of the pore size of supported microporous inorganic films and of their penetration into the macropores of the ceramic support are crucial goals in Harold's synthesis of ceramic membranes.

One of the most successful programs developed in the transport area is Julio Ottino's program in fluid mechanics and mixing. His research has raised the level of understanding in mixing to the point where, for the first time, it is possible to view many seemingly unrelated problems within the context of a single theory.

### **Applied Theoretical Chemistry**

In many new areas it is becoming critically important to incorporate details of molecular-scale chemical physics into engineering models. The department has research efforts that address this need. Much of the work represents an emerging effort that will likely be a future core strength for the department and the profession.

Michael Cook is developing and using density functional methods for the study of point defects in materials. An important application is to electronic device materials such as silicon and III-V semiconductor alloys and compounds. He is also investigating the nature of potential-energy surfaces for free radical reactions as a means of providing a more firm foundation for kinetic models. Peter Monson's research is concerned with applications of fundamental statistical thermodynamics, especially in the context of phase equilibria and the properties of interfa-

cial systems. He has developed new approaches to studying the influence of molecular shape and polarity upon fluid phase equilibria. This work is now being extended to prediction of solid-liquid equilibria. His group is also exploring the molecular basis of adsorption separations in terms of the nature of the intermolecular forces and the adsorbent microstructure. Fundamental theoretical studies of the molecular structure of fluid films on solid surfaces are also being carried out. Phil Westmoreland's research stands at the interface between detailed molecular theory and process reaction engineering. He co-developed Bimolecular Quantum-RRK analysis to predict rate constants and product channels for gas-phase association reactions in combustion. Westmoreland is exploiting this method in pyrolysis, combustion, and plasma chemistry while probing more complex potential-energy surfaces and intermolecular energy transfer.

### **THE FUTURE**

As this article is being written, the department is in the middle of several new initiatives that promise to significantly improve our programs. We are a major participant in the University/Digital Equipment Corporation PILGRIM project, which is a \$6 million project to design, install, and test a network of several hundred high-performance workstations in the College of Engineering and in the Computer and Information Science Department. So far the department has installed twenty workstations for research purposes and has access to a workstation classroom for teaching. Several courses will use workstation-based software to complement lecture material, including the design courses, the separations course, and the statistical thermodynamics course.

The undergraduate program continues to evolve, and it embraces a major commitment to upgrading the lab. We began converting many of the laboratory experiments to computer data acquisition and control some time ago with a generous donation of process control computers from Analog Devices (see *Chem. Eng. Ed.*, **24**, 106, 1990). Over the next two years we will design and build new experiments on crystallization, process control, and polymerization kinetics. Many of the older PCs used for on-line data acquisition and control will be retired and replaced by more modern machines. We continue to explore ways of inserting more chemistry and solid-state material into the curriculum, and two of the faculty intend to write books on these topics as that activity matures.

The department has grown into a vigorous, vibrant place in only forty years of existence, presently with eight of the thirteen faculty also at forty or under. By the time we reach our half-century in the year 2001, we hope to make our perspective a vital part of chemical engineering. □

# DEVELOPMENT AND USE OF OPEN-ENDED PROBLEMS

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**A**t the 1987 summer school for chemical engineering faculty, sponsored by the American Society for Engineering Education, a common theme was the call for more open-ended problems in course work. Suggestions for developing and using such problems are presented in this paper. This is done by considering various examples from courses on mass and energy balances, communications, kinetics and ideal reactors, and reactor design. The benefits of using open-ended problems, from both instructor and student perspectives, are presented. Difficulties which may be encountered by the instructor and students are also discussed. A rather broad definition of open-ended is used here, namely something which goes beyond the *given this and this, calculate that* type of problem for which there is typically only one answer.

## PROBLEM DEVELOPMENT

Various avenues are available to obtain a variety of open-ended type problems:

- application of research findings
- sharing problems with colleagues
- selection of appropriate problems from the course text
- consulting other reference texts
- modification of traditional-type problems
- development of new problems

The following sections contain several illustrations of these different approaches. The examples are open-ended to varying degrees and therefore

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***The examples are open-ended to varying degrees and therefore represent different levels of challenge for students. . . . In all cases, the intent is to promote and encourage creativity and an inquisitive nature.***

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*Paul Amyotte received his BEng from the Royal Military College of Canada, his MSc (Eng) from Queen's University, and his PhD from the Technical University of Nova Scotia (TUNS). He is an associate professor and head of the chemical engineering department at TUNS. His interests are fluidized-bed drying, gas and dust explosions, and engineering education.*



represent different levels of challenge for students. Some are intended to be fun and some are of a more serious nature. In all cases, the intent is to promote and encourage creativity and an inquisitive nature.

## ***Application of Research Findings***

From time to time, elements of the author's research program on dust explosions have found their way into the classroom in the form of tutorial discussions and home assignments.

Briefly, explosion tests are conducted in a spherical vessel having a volume of 26 L. Dust dispersion through a perforated nozzle is achieved by an air blast from a 1-L reservoir. Prior to each run, the explosion vessel is partially evacuated so that the dispersion pulse brings the vessel pressure up to 1 bar at the time of ignition. Ignition is by a single spark passed between two fixed electrodes or by a more energetic chemical ignitor. Pressure development over the course of an explosion is measured by a piezoelectric transducer mounted flush with the interior of the vessel.

Useful discussions (in the mass and energy balances course) on process variable measurement and data analysis have arisen by asking the following open-ended questions:

- *How might you record the pressure measurements from the piezoelectric transducer?*

[Pressure-time traces acquired by an oscilloscope and by a personal computer are made available either after discussion or to stimulate discussion if required.]

- How could you determine the maximum rate of pressure rise and the maximum explosion pressure from one of these pressure-time traces? How accurate will these values be?

[These questions can lead to a discussion on mechanical and computer methods for determining slopes and maxima of curves.]

- How could you determine the pressure required in the explosion chamber prior to dust dispersal (so that the pressure at the time of ignition is 1 bar)?

[Typical responses to this question have included (a) by trial-and-error experimentation, and (b) by consideration of the dispersion reservoir and explosion vessel together as the system, with application of Boyle's law to the initial (pre-dispersion) and final (post-dispersion) states.]

Scanning electron micrographs of the same coal dust before and after an explosion test have been used in the kinetics and ideal reactors course to initiate discussion on the nature of reacting heterogeneous systems. Two simple questions can accomplish this:

- Do you see any similarities between the "before and after" pictures?  
[e.g., particle size]
- Do you see any differences between the "before and after" pictures?  
[e.g., particle shape and degree of fragmentation]

The use of rupture disks and relief valves on storage vessels and chemical reactors has been introduced in the reactor design course by a walk through our dust explosion research laboratory. The vessel previously described is fitted with a rupture disk, and thus is a good example of one method of vessel or process protection. The discussion which follows this tour is filled with *what if's* (e.g., . . . the rupture disk bursts? . . . a dust with unknown explosion parameters is being investigated?) and *how come's* (e.g., . . . the vessel has a rupture disk and not a relief valve? . . . the rupture disk is vented upward into a fume hood?) which ordinarily might not have arisen.

### Sharing Problems with Colleagues

Many instructors have a collection of problems contributed by their colleagues. One of the author's favorites in the open-ended category is the following, drawn from the mass and energy balances course:

Formaldehyde is made by the catalytic air oxidation of methanol. When the process is operating properly, the mole ratio of air to methanol in the feed is about 6:1, and the conversion (moles of formaldehyde in product stream per mole of methanol fed) is 30 mole %. There is an unexplained drop in the conversion, and a complete analysis of the product stream is ordered. The analysis gives the following mole percentages: N<sub>2</sub> (63.1), O<sub>2</sub> (13.4), H<sub>2</sub>O (5.9), H<sub>2</sub>CO (4.1), CH<sub>3</sub>OH (12.3), and HCOOH (1.2). The formic

## The use of rupture disks and relief valves on storage vessels and chemical reactors has been introduced in the reactor design course by a walk through our dust explosion research laboratory.

acid is formed by the undesired but unavoidable oxidation of some of the formaldehyde. This phenomenon accounts for the conversion of methanol to formaldehyde being only 30 mole % even under normal conditions. Calculate the new conversion and suggest reasons for the sudden drop in conversion.

The calculation of the new conversion (23%) is relatively straightforward. On the basis of an air-to-methanol feed ratio of 4.6 (instead of 6), the sudden drop in conversion may well be due to a drop in the air feed rate. However, the possibilities of a reduction in catalyst efficiency and a drop in methanol feed rate cannot be ruled out entirely.

### Selection of Appropriate Problems from the Course Text

The following problem used in the kinetics and ideal reactors course is taken from Fogler:<sup>[1]</sup>

The frequency of flashing of fireflies and the frequency of chirping of crickets as a function of temperature are given below:

For fireflies:

Temperature (°C)	21.0	25.0	30.0
Flashes per minute	9.0	12.16	16.2

For crickets:

Temperature (°C)	14.2	20.3	27.0
Flashes per minute	80	126	200

What do these two events have in common?

"The" solution from a kinetics point of view is that the flashing and chirping frequencies both exhibit an Arrhenius dependence with temperature, and both have the same activation energy. However, a simple linear relationship correlates each set of data, as does the frequency as a function of temperature squared. Maybe an analogy with the specific heat of a gas is in order. Perhaps a suitable question to ask is: "Would more data on the two events help to clarify the frequency/temperature relationship?"

### Consulting Other Reference Texts

The following exercise was given in the communications course, but was drawn from the mass and energy balances text (Felder and Rousseau<sup>[2]</sup>):

I have given you the task of measuring the volumetric flowrate of a liquid in a large pipeline. The liquid is in turbulent flow, and a flat velocity profile may be assumed

(so that you need only measure the fluid velocity to determine the volumetric flowrate). The line is not equipped with a built-in flowmeter; however, there are taps to permit the injection or suspension of devices or substances and the withdrawal of fluid samples. The pipeline is glass and the liquid is clear. Assume that any device you want to insert in the pipe can be made leakproof if necessary, and that any technique you propose can be calibrated against known flowrates of the fluid.

Come up with several ways of performing the measurement that might have a chance of working. (Examples: insert a small salmon in the pipe, suspend a lure irresistible to salmon upstream of the injection point, and time how long it takes the fish to travel a measured section of the pipe; or, use a laser Doppler velocimetry system.) The techniques you propose must be substantially different from one another; giving me a pitot tube with ten different manometer fluids will get you nowhere. Good luck!

Student responses, reported in memorandum form, included:

- Use a vane anemometer, hot-wire anemometer, venturi meter, rotameter, pitot tube, orifice plate.
- Use the marker method, with blueberries or ping-pong balls (negligible weight) as the marker.
- Fill a small balloon with the same fluid as in the pipeline, place it in the pipe, and note the time for a specific distance travelled.
- Insert a particle and measure its velocity with a radar gun.
- Insert a steroid-injected track star into the pipe, complete with diving gear and speedometer. Have him run until he feels no liquid pressure on his back and then measure his velocity with the speedometer.
- Install a small turbine and generator and measure the energy output.
- Tie a lump of sugar to a string and insert it into the flowing liquid. Measure the time required to dissolve the sugar.

### Modification of Traditional-Type Problems

The prescribed text (Blicq<sup>(31)</sup>) for our communications course contains several assignments which consist of a descriptive passage followed by an instruction to write a specific type of report (incident, field trip, etc.) based on the given scenario. These exercises are helpful in establishing the fundamentals of report writing, and they provide the students and instructor with a given set of data with which to work. On the negative side for the students is the fact that these data are totally unfamiliar to them. There is also the temptation to regurgitate the narrative passage from the text in a slightly different sequence.

A possible modification is to leave out the scenario description, thus allowing the students to fill in the details themselves. Consider the following assignment:

**Write an incident report (in memorandum form) on something that has happened to you in the past year or so.**

The reports should be structured according to the scheme of summary, situation, event, and outcome, but the specific nature of each report will be different. If a particular report is well-written, then the instructor should have very few questions after reading about an incident of which he previously had no knowledge.

Here is another case of problem modification (from the kinetics and ideal reactors course), this time by leaving out a piece of information. The original problem from Fogler<sup>(1)</sup> is:

The rule of thumb that the rate of reaction doubles for a 10°C increase in temperature occurs only at a specific temperature for a given activation energy. Show that the relationship between activation energy and temperature for which the rule holds is

$$T = \left[ \frac{(10K)E}{R \ln 2} \right]^{1/2}$$

Neglect any variation of concentration with temperature.

The problem can be reworded so that the exact relationship is not given and the students are not forced down a pre-determined solution path:

There is a rule of thumb which states that the reaction rate doubles for every 10°C increase in temperature. This is true, however, only at a specific temperature for a given activation energy. Develop a relationship between activation energy and temperature for which the rule of thumb holds. Any variation of concentration with temperature may be neglected.

Practically all students will start out with a ratio of Arrhenius expressions:

$$\frac{k_1}{k_2} = \frac{A \exp(-E/RT_1)}{A \exp(-E/RT_2)}$$

where  $k_2 = 2k_1$  and  $T_2 = T_1 + 10K$ .

Some will stop at

$$T_1(T_1 + 10K) = \frac{(10K)E}{R \ln 2}$$

A few will go on to solve the quadratic for  $T_1$ . Only a very few will approximate  $T_1(T_1 + 10K)$  by  $T^2$  to arrive at

$$T = \left[ \frac{(10K)E}{R \ln 2} \right]^{1/2}$$

An add-on statement to an existing problem can sometimes provide a bit of an open-ended nature. The following problem (mass and energy balances course) from Felder and Rousseau<sup>(2)</sup> was modified by the addition of part (b):

In the Deacon process for the manufacture of chlorine, HCl and O<sub>2</sub> react to form Cl<sub>2</sub> and H<sub>2</sub>O. Sufficient air (21 mole %

O<sub>2</sub>, 79% N<sub>2</sub>) is fed to provide 25% excess oxygen, and the fractional conversion of HCl is 70%.

- (a) Calculate the mole fractions of the product stream components.
- (b) Why do you think 25% excess oxygen is used in this process?

Student answers to part (b) have included:

- To provide additional flow material for intimate mixing of the reactants
- To help control the reaction
- To increase the conversion of HCl, which is the valuable reactant, at the expense of air which is cheap and readily available
- To minimize the occurrence of undesirable side reactions
- To control the reaction temperature

In a similar manner, this problem (mass and energy balances course) from Luyben and Wenzel<sup>[4]</sup> was modified by the addition of part (b):

A coal containing 81 mass % carbon and 6 mass % unoxidized hydrogen is burned in dry air. The rest of the coal is solid inert. The amount of air used is 30% more than is theoretically required to completely oxidize all of the carbon to CO<sub>2</sub> and all of the hydrogen to H<sub>2</sub>O.

- (a) Calculate the number of kg of air per kg of coal, and the composition of the stack gas leaving the furnace, assuming this gas contains no CO.
- (b) Is this a realistic coal?

Student answers to part (b) have included:

- No; there should be some water content. A realistic coal would also likely contain sulfur, nitrogen, and oxygen.
- No; a realistic coal is more likely to undergo incomplete combustion.
- No; the majority of coals have some percentage of oxidized hydrogen.
- Yes; the general composition of the coal is of the order of 80-85% carbon and 4-5% hydrogen. However, the fact that the rest of the coal is inert may be questionable.
- It all depends; for run-of-mine coal, the inert solid (ash) percentage is probably too low; for clean coal it's probably too high.
- It all depends; for an approximate mass balance calculation, the coal composition may be alright. For any detailed work based on the coal analysis, the coal should not be considered realistic.

### Development of New Problems

Tired of marking the same thing over and over, the author gave the following assignment in the communications course:

What bugs you? Respond in memorandum form.

The response was overwhelming, humbling, and certainly enlightening. Replies ranged from the frivolous to the serious:

- Slow drivers in the fast lane
- The quality of food services at some universities
- Girlfriends who don't appreciate the amount of time an engineering student must work

- The lack of cartoon shorts before feature movies
- Noisy roommates who don't attend summer term
- Power outages during computer usage
- Racism

Another example in this category is:

Pose and solve a short mass balance problem drawn from everyday life. The concept need not be difficult; however, it should be something which illustrates, in a non-technical manner, the mass balance principle.

This question was given as part of a take-home test and produced several interesting problems, such as the one below.

A civil engineering survey showed that 1,000 vehicles enter the Mic Mac Rotary (a local area of traffic congestion) during the time period from 4:00 pm to 5:00 pm. Out of every ten vehicles, one is a truck and the rest are cars. It is Friday afternoon and all vehicles are coming from the new bridge via the Circumferential Highway (the only source of vehicles). Several civil engineers stood in the middle of the rotary (they had nothing better to do) and counted what vehicles used which exit. They then gave their data to a chemical engineer who put them into the following table:

Prince Albert Road	100 vehicles
Circumferential Highway (to Woodside)	500 vehicles (15% trucks)
Main Street	200 vehicles (5% trucks)
Waverly Road	186 vehicles (6.5% trucks)

NOTE: Trucks were not allowed to exit via Prince Albert Road due to construction.

- a) Draw the fully labeled flow diagram of the rotary.
- b) What is the composition of each exit?
- c) Is anyone lost in the rotary during this hour?
- d) If yes, how many cars and trucks are lost? Why are they lost?

The final example considered here is a mass balance problem involving data consistency checks which was developed by the author and two of his colleagues (Furter, *et al.*<sup>[5]</sup>):

- a) A process steam boiler (operating at steady state) at a coal conversion plant fires coal gas from a continuous vertical retort. The fuel analysis is given in Table 1 (see Reference 5). An environmental test crew has made measurements of the flue gas emissions in the stack; the measured dry flue gas analysis is given in Table 2 (see Reference 5). Over the duration of the testing, the molal humidity of the combustion air supply was 0.05 mole moisture per mole dry air. Using the law of conservation of mass, check the consistency of the data.
- b) The boiler described in part (a) operates at a thermal input of 25 MW, and the higher heating value of the fuel gas has been determined as 17.97 MJ/m<sup>3</sup> at 15°C and atmospheric pressure. In addition to determining the dry flue gas analysis, the environmental test crew has made several other measurements. The temperature of the flue gas was found to be 325°C. A particulates traverse revealed negligible stack solids, a flue gas moisture content of 38% by volume, and a stack gas velocity of 5.75 m/s. The chimney diameter is known to be 2.06 m, and

the burners were thought to be operated with about 17% excess air over the duration of the testing. Using the law of conservation of mass, check the consistency of the data.

In solving this problem, the student encounters several questions:

- What do you do when the left-hand side of a mass balance expression does not equate with the right-hand side?
- Could the measured data be incorrect?
- Is there a plausible explanation for the situation where more of a component exits a system than enters?

## PROBLEM USE

### *Incorporation*

Some suggestions for incorporating open-ended problems in a course include:

- Offer exposure to open-ended problems in class tutorials and home assignments before using them on tests and exams.
- For in-class and home exercises, gradually increase the degree of difficulty and encourage students to consult one another.
- Get the class to brainstorm through a problem and encourage volunteers to lead the discussion (several helpful suggestions for developing a "group-based Socratic approach" have been given by Felder<sup>(6)</sup>).
- Give a problem to the class and let them go away and think about it; start the next lecture by raising the problem again.
- Start out with low credit for open-ended problems, and gradually increase the credit.
- In addition to building the credit and difficulty of the problems, increase the number of open-ended problems as the course goes on.
- Use open-ended problems in as many courses as possible, and encourage colleagues to do the same.
- Provide a very open-ended experience in design and thesis courses.
- Use closed-ended problems to establish the fundamentals and allow the students to gain confidence in their abilities.
- Discuss problem-solving techniques and skills (see, for example, Fogler<sup>(1)</sup>).

### *Difficulties*

From a student's perspective, some potential problem areas include:

- They are generally not used to dealing with open-ended problems.
- It is easy to be intimidated and become frustrated (hopefully, only initially) by what appear to be "trick" problems. There is also likely to be a feeling of "Boy, I

could never come up with that (*i.e.*, the solution) by myself" (which is quite often not true).

- They want to ask the instructor many questions about possible solutions. (The key is to get them to ask themselves these questions.)
- The students may not be used to having the following conversation:

Student: "What's the right answer?"

Instructor: "I don't know. I don't think there is one."

From an instructor's perspective, some potential problem areas include:

- It can be time-consuming to develop open ended problems, particularly from scratch.
- It can also be time-consuming to grade solutions to such problems.
- The instructor must become almost a "cheerleader" at times.
- The instructor may not be used to having the following conversation:

Student: "What's the right answer?"

Instructor: "I don't know. I don't think there is one."

### *Benefits*

Among the many benefits of open-ended problems, the author has experienced the following:

- Developing intangible communication skills such as cogently expressing an opinion and thinking on one's feet.
- Appealing to various types of students, not just those who are satisfied with number crunching and application of formulas.
- Giving the students a chance to be creative.
- Allowing the students to write on topics which are relevant to their daily lives.
- Demonstrating that mass and energy balances are more than just exercises in algebra.
- Providing a lead-in to discussion of items such as instrumentation and measurement accuracy.
- Preparing the students for the open-ended type problems they can expect in the future.
- Educating the instructor as to the unique abilities of some engineering students.

## CONCLUSION

Various examples of open-ended problems and ways to obtain them have been presented in this paper. Suggestions for incorporating open-ended problems and some of the benefits and difficulties encountered in using such problems have been discussed. In the author's opinion, these benefits far outweigh the difficulties. Open-ended problems are invaluable for developing and fostering basic skills,

once these skills have been established through means such as closed-ended problems.

## REFERENCES

1. Fogler, H.S., *Elements of Chemical Reaction Engineering*, Prentice-Hall, Englewood Cliffs, NJ (1986)
2. Felder, R.M., and R.W. Rousseau, *Elementary Principles of Chemical Processes*, second edition, Wiley, New York, NY (1986)
3. Blicq, R.S., *Technically - Write!*, third edition, Prentice-Hall, Scarborough, Ontario (1987)
4. Luyben, W.L., and L.A. Wenzel, *Chemical Process Analysis: Mass and Energy Balances*, Prentice-Hall, Englewood Cliffs, NJ (1988)
5. Furter, W.F., M.J. Pegg, and P.R. Amyotte, "A Practical Application of Mass Balances," *Chem. Eng. Ed.*, **23**, 163 (1989)
6. Felder, R.M., "Stoichiometry Without Tears," *Chem. Eng. Ed.*, **24**, 188 (1990) □

## ChE book review

### ELEMENTARY GENERAL THERMODYNAMICS

by M.V. Sussman

Reprint Edition with Corrections; Robert E. Krieger Publishing Co., PO Box 9542, Malabar, FL 32902; 478 pages, \$52.50 (1989)

Reviewed by

Amyr Teja

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This is a reprint edition of the book first published in 1972 by Addison-Wesley Publishing Co. The new printing corrects a large number of typos in the original edition and provides more exposure to SI units. There are also a number of minor additions to the text, such as a brief mention of the Design Institute of Physical Properties Research (DIPPR) publications and even references to estimation methods for thermodynamic properties. In all other respects, however, this version of the book is identical to the original.

The book is designed as a broad introduction to thermodynamics and its many applications to engineering and science. Thus there are the usual chapters on the first and second laws (Chapters 2 and 3), power and refrigeration cycles (Chapter 4), relationships among thermodynamic properties (Chapter 6), equations of state (Chapter 7), fugacity and activity (Chapter 8), thermodynamics of mixing and composition change (Chapter 9), and chemical equilibrium (Chapter 10).

In addition to the above, however, there are also introductory chapters on statistical thermodynamics (Chapter 5) and irreversible thermodynamics (Chapter 11). Moreover, there are sections on nuclear energy, electrochemical processes, and fuel cells

which are not generally found in introductory textbooks of thermodynamics.

Not unexpectedly, the breadth of coverage comes at the expense of depth. Thus, the discussion on cubic equations of state stops at the van der Waals equation, with a brief mention of the Redlich-Kwong equation but no mention of the other variants widely used in chemical engineering process calculations. Also, none of the modern analytic versions of the corresponding states principle are described. More importantly for chemical engineers, only the van Laar equation is discussed as a solution to the Gibbs-Duhem equation, and none of the recent activity coefficient models are mentioned. The section on fluid phase equilibria is therefore all too brief. Finally, statistical thermodynamics is only discussed from the point of view of providing a molecular explanation of entropy, and the reader is not given any indication that it could lead to, for example, equations of state for real fluids.

Nevertheless, the book achieves reasonable depth in many cases and offers a possible alternative to the texts more specifically designed for chemical engineers. It is particularly suited to students who are introduced to thermodynamics in their sophomore or even their freshman years. It appears to be suitable as a self-teaching text because it makes liberal use of worked examples and certainly provides a broader view of the applications of thermodynamics. Perhaps it could serve as a supplementary text in undergraduate chemical engineering thermodynamics courses. Students will certainly find reading it worthwhile. □

## ChE books received

*Understanding Process Integration II*, by R. Smith; Hemisphere Publishing Corp., 79 Madison Ave., New York, NY 10016-7892; 360 pages, \$79.50 (1988)

*Thermo- and Laser Anemometry*, by Polyakov; Hemisphere Publishing Corp., 79 Madison Ave., New York, NY 10016-7892; 173 pages, \$40.00 (1988)

*Basic Concepts of Chemistry* (Third Edition), by Leo J. Malone; John Wiley and Sons, 1 Wiley Drive, Somerset, NJ 08875-1272; 682 pages, \$42.50 (1989)

*Chemical Information: A Practical Guide to Utilization*, 2nd Edition, by Yecheskel Wolman; John Wiley & Sons, Inc., 1 Wiley Drive, Somerset, NJ 08875-1271; 291 pages, \$44.95 (1988)

*Chemistry: Experiment and Theory*, Second Edition, by Bernice G. Segal; John Wiley & Sons, Inc., 1 Wiley Drive, Somerset, NJ 08875-1272; 1008 pages, \$49.22 (1989)

*Engineering Applications Software Development Using FORTRAN 77*, by G. A. Moses; John Wiley & Sons, 1 Wiley Drive, Somerset, NJ 08875-1272; 320 pages, \$39.95 (1988)

# AN INTRODUCTION TO EQUILIBRIUM THERMODYNAMICS

## *A Rational Approach to Its Teaching*

### PART 2: Internal Energy, Entropy, and Temperature<sup>1</sup>

DONALD F. WILLIAMS, DAVID GLASSER  
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In Part 1 of this paper, we introduced notation for functions and their derivatives, and through using this notation, we formulated a purely mathematical background, based on the properties of functions. We shall now show an approach that may be used to introduce the fundamental ideas of thermodynamics.

We start by explaining to the students that the purpose of thermodynamics is to enable us to correlate and predict the behavior of real systems containing matter. In doing this, we shall use the mathematical background which was formulated in Part 1, together with a knowledge of the behavior of matter (which is studied in such subjects as physics and applied mathematics).

Additionally, we will need to make some basic



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*David Glasser is a professor of chemical engineering at the University of the Witwatersrand. He holds degrees from the University of Cape Town and Imperial College (London). His main areas of interest are reaction engineering and mathematical modeling. He has been interested in teaching thermodynamics ever since he first became involved after being "made an offer" as the most-junior member of the academic staff.*



<sup>1</sup> Part 1 of this paper, "Notation and Mathematics," was published in *CEE*, Vol 25, No 2 (Spring 1991).

assumptions or axioms, which we have labeled below as "postulates." There can be no *a priori* justification or "proof" of such postulates, and some of them may seem at the time to be rather peculiar. The only reason for using these assumptions rather than others is that the equations which result seem, from experience, to be useful in our stated purpose of predicting the behavior of matter-containing systems.

This state of affairs is similar to the exposition of Euclidean geometry, where we first had to accept a number of axioms (such as "parallel lines never meet," and "vertically opposite angles are equal"). We could then develop a succession of theorems (many of which have results which now seem second nature to us) which have proved to be useful in many areas of the science of measurement. Alternative sets of axioms (such as, for example, "parallel lines *do* meet") lead to the development of alternative (non-Euclidean) geometries, some of which are, in fact, found to have uses in other areas.

#### **Physical Background**

We should agree, before we begin, that we have an understanding from physics of the concepts of *length, time, and mass*, to which we shall add the chemical concept of the measurement of amount of material in number of *moles* rather than mass.

The concept of length extends readily to give us *area* and *volume*. Combined with time, it gives us the concepts of *velocity* and *acceleration*. From mass and acceleration (or from momentum, obtainable from mass and velocity) we may obtain the concept of *force*. From force and area we obtain *pressure*, and from force and length we obtain *work*. We therefore assume that we have a common agreed-upon understanding of these ideas, which we shall not bother to

define more fully at this point.

We shall need to consider a number of "thought experiments" involving these concepts. Some of these we could actually perform; others are somewhat idealized, so that it might be difficult to set them up exactly in practice. But we should have no difficulty in envisaging the outcome of these procedures. In some of them we shall need the concept of *temperature*. It is more difficult to agree upon an exact quantitative definition of temperature at this point, but we should be able to agree that we have common concepts of "hotter" (= higher temperature) and "colder" (= lower temperature).

### Conservation of Energy

Our basic primary axiom is that energy is conserved. We can no more prove this than we can any of the other postulates which we shall make below, although we may perhaps take comfort in the successful description of the behavior of matter in the vast amount of science (in addition to thermodynamics) which has as its basis the Principle of Conservation of Energy.

We now need to develop a quantitative mathematical expression of this principle. We might start by saying that if energy is conserved, the energy of a body or system in state 2 must be the same as it was in state 1, which we might express as

$$E_1 = E_2 \quad (42)$$

Now, what terms go to make up the energy  $E$ ? If we consider experiments which we might make with falling stones or moving projectiles, experiment would lead us to conclude (in an idealized situation) that the energy of these bodies was made up of the sum of the two separately identifiable forms of energy which we call kinetic and potential energies. Thus, we could re-write Eq. (42) as

$$E_{K1} + E_{P1} = E_{K2} + E_{P2} \quad (43a)$$

or

$$\Delta E_K + \Delta E_P = 0 \quad (43b)$$

where we are assuming the usual definitions that  $E_K = \frac{1}{2}mv^2$  and  $E_P = mgh$ .

Consideration of the state of affairs when we raise our stones by hand (increasing their  $E_P$  without changing  $E_K$ ) or proceed to throw them (increasing their  $E_K$  without decreasing  $E_P$ ) shows that this formulation is inadequate. We need to invent a concept of the transfer of energy *to* the body (or system) under consideration from an external source. Giving this concept the symbol  $w$ , we may extend Eq. (43b) to

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*We start by explaining to the students that the purpose of thermodynamics is to enable us to correlate and predict the behavior of real systems containing matter.*

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$$\Delta E_K + \Delta E_P = w \quad (44)$$

(Of course, the Principle of Conservation of Energy still applies overall since the corresponding equation for our hand or other source of the energy term  $w$  will be  $\Delta E - w = 0$ .) We find that Eq. (44) is now an adequate description of these cases if we use a  $w$  value calculated from

$$w = \int \mathbf{f} \cdot d\mathbf{x} \quad (45)$$

(where  $\mathbf{f}$  is the force applied over distance  $\mathbf{x}$ ). We may thus identify  $w$  with our prior concept of *work*.

But now consider what happens when our flying objects hit the ground, or an immovable wall, losing their  $E_K$  and  $E_P$  without any  $w$  being apparent. We are forced either to abandon the Principle of Conservation of Energy, or (noting in passing that bodies in such situations are observed to get hotter) to conclude that the energy which is "missing" from the terms of Eq. (44) must still be present in another form. We invent the concept of "energy of state" or "internal energy" to account for this energy. Giving this new concept the symbol  $U$  and extending Eq. (44) to account for it, we obtain

$$\Delta E_K + \Delta E_P + \Delta U = w \quad (46)$$

We shall not continue the argument further at this point, but will merely note that further additions to the left-hand side of Eq. (45) may be necessary in situations where energy is present in forms which we have not accounted for. Terms such as magnetic, electrostatic, or surface energies may need to be introduced (or these may be regarded as an extension of the concept of potential energy).

We find by experiment that if we put a fixed amount of some specific material (such as oxygen gas) into a well-insulated enclosure, we can totally define the properties of the material if we know two of the variables, such as the values of the pressure and volume. That is, whatever happened before, if we know the "state of the system" (*i.e.*, the values of the pressure and volume), then we know that the values of other variables (such as density, refractive index, and thermal conductivity) will be uniquely determined. In other words, we know that these

other variables are a function of pressure and (specific) volume only.

It turns out in practice that not all pairs of variables are equally good for *uniquely* determining the state of the system. For example, pressure and volume will not uniquely determine the state of liquid water close to 4°C, where the density goes through a maximum. Thus, our postulates will later be made in terms of specific pairs of variables which do not have such problems associated with them.

Now consider an experiment such as the one shown in Figure 1a. Material contained in a well-insulated enclosure may be agitated by the stirrer or acted upon by the piston. The movements of the piston and the stirrer shaft both involve work which we may measure in terms of our accepted concepts of force-times-distance (or the straightforward extension to torque-times-rotation). The pressure and volume of the material in the container are also measurable quantities.

Now consider the changes in P and V which we may obtain in this apparatus. (For this purpose it may be easier to first consider the contents to be a gas—but similar, more complex, apparatus could at least be envisaged for other materials.) By pushing or pulling on the piston we may change the P and V of our gas along curved lines such as those shown in Figure 1b. (If we had an ideal gas, these would be the lines  $PV^\gamma = \text{constant}$ .) By rotating the stirrer with the piston held fixed, we find that we increase the temperature, and hence the pressure, at a fixed volume.

By utilizing suitable portions of such paths, we find that not only can we move (in one direction, anyway) between any pair of points, but we can also, in fact, do so by a variety of different paths. Figure 1b shows two of the infinitely many paths from point 1 to point 2. For each path, we may measure the sum of the work done by the stirrer and the piston. We find that, for fixed final and initial points, the total work required is a constant, irrespective of the path taken.

Now consider the energy conservation equation, Eq. (46). Since there are no changes in the kinetic or potential energies of our stationary apparatus, the equation in this case reduces to

$$\Delta U = w \quad (47)$$

Thus, it appears that our concept of "internal energy" U is a useful one, in that U turns out to be a "state function"; that is,  $\Delta U$  depends only on the

initial and final states, not on the path. By choosing some arbitrary reference state (say,  $P_0, V_0$ ) and assigning it a value of U (say,  $U_0 = 0$ ), we may by a suitable experiment measure the value of U at any other (P,V) point. Therefore we need have no further "understanding" of the nature of our quantity U; it is sufficient that we can measure it (and that it will prove in due course to be a useful concept for our purpose).

However, if we perform these experiments in an apparatus that is not well insulated, all our carefully thought-out theory appears to collapse. Indeed, in some cases an apparatus left in state 2 may return to another state without the performance of any work w. Rather than abandon the Principle of Conservation of Energy, we conclude that there must be other ways than work of transferring energy to the system. We give this means of transferring energy the symbol q, and Eq. (46) becomes

$$\Delta E_K + \Delta E_P + \Delta U = w + q \quad (48)$$

We may obtain quantitative values of q from experiments in an apparatus such as the one shown in Figure 2. From experiments performed as in Figure 1, we may obtain the  $\Delta U$  value for any change. Thus (theoretically at least) we know the dependence of U on P and V, which is the function  $U^{PV}$ . The energy balance for experiments conducted as in Figure 2 may be rearranged to give

$$q = \Delta E_K + \Delta E_P + \Delta U - w \quad (49)$$

Experiments (or processes) for which Eq. (46) (or Eq. 47) is an adequate description are termed *adiabatic* processes and need to be surrounded by perfectly insulating or adiabatic surfaces. Those in which it is necessary to allow for the energy transfer term q are said to be *non-adiabatic*, and the surfaces which permit energy to be transported through them

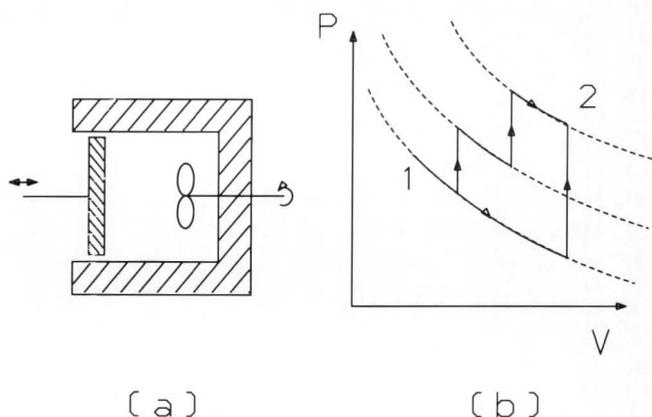


FIGURE 1. System with work terms.

in this fashion are called *diathermal*.

We note from experience that the energy transfer term  $q$  occurs when our (non-adiabatic, or un-insulated) system and its surroundings are at different temperatures, and we give  $q$  the name *heat*. One should be careful about the fact that heat  $q$  is an energy *transfer* mechanism, not a form of energy itself. Once energy has entered a system in this fashion, it is indistinguishable from energy that entered as work. It is incorrect to expect to be able to find the "heat" inside the system. Terms such as "heat content" or "conversion of heat into work" are misleading; they are based upon a misunderstanding of the equivalent roles of heat and work as energy transfer mechanisms. Because of the fact that both  $q$  and  $w$  refer to energy transfer processes rather than to quantities of some substance (caloric!), it is convenient to emphasize this by calling  $q$  "heating" and  $w$  "working." This has the advantage of being related to the words used by other authors, but emphasizing the process aspect.

Neither  $q$  nor  $w$  is, of course, confined to adding energy to the system. Both are also possible ways for energy to leave the system. Thus, if the piston in Figure 1 or 2 moves so as to increase the volume, it actually has work done on it by the contents of the apparatus, the energy of which therefore decreases. We also know that if the non-adiabatic apparatus is hotter than its surroundings, it will lose energy as heat to the surroundings.

If we use different amounts of substance in our experiments in order to determine  $U^{PV}$ , we will obtain different relations (or surfaces in  $U$ - $P$ - $V$  space). We find, however, that we may reduce these all to one surface by considering not volume  $V$ , but *molar volume*, given by  $\hat{V} = V/N$ , where  $N$  is the number of

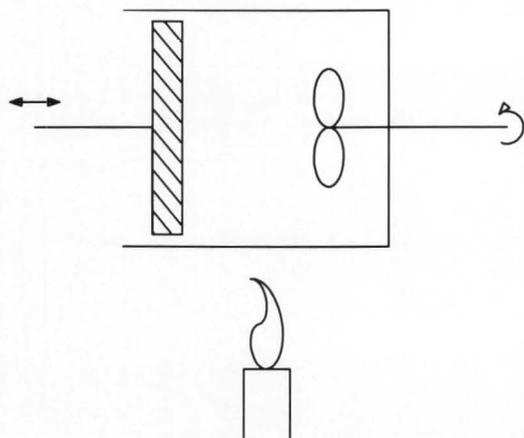


FIGURE 2. Apparatus for measuring  $q$ .

moles of material involved. This gives us values of *specific internal energy*, or *molar internal energy*, i.e.

$$\hat{U} = \hat{U}^{PV} \quad (50)$$

We say that  $U$  is an *extensive* property, which depends on the amount of material present, while  $\hat{U}$  is an *intensive* property, which depends only on the state (or condition) of the matter, not on how much there is.

In Part 1 of this paper, we assumed a function  $U^{SV}$  and showed that this leads to Eq. (28)

$$(\Delta U)_1 = \int TdS - \int PdV = Q + W \quad (28)$$

From our experiments, we have now obtained (for processes where  $\Delta E_k = \Delta E_p = 0$ ) the relationship

$$(\Delta U)_2 = q + w \quad (51)$$

Here we have used the subscript 1 to identify the value from the equations of Part 1, and the subscript 2 to identify the physical values from our experiment. The work term  $w$  results from the displacement of the point of action of a force, or  $w = \int \mathbf{f} \cdot d\mathbf{x}$ . Suppose the process under consideration changes under the influence of driving forces which are so small that it is effectively in equilibrium at each stage (such a process is termed *reversible*). It is then easy to show from physical considerations that this (force-times-distance) term may be expressed (in the absence of work terms such as that for the stirrer in Figure 1) as  $-\int PdV$ .

We now choose to equate  $(\Delta U)_1$  and  $(\Delta U)_2$ ; that is, we regard our internal energy  $U$  as the function  $U^{SV}$  of Part 1. This is in line with our experimental finding that the state of a system depends only on two independent variables. The ones we used before were  $P$  and  $V$ , but once we have any two we can easily change them to any other two with which there is a monotonic relationship. (The reader need not be disturbed by the fact that we have not yet identified the variable  $S$ .) We may choose to identify the  $V$  terms of both Part 1 and Part 2. Now consider a series of experiments performed in the apparatus of Figure 1, but *without* using the stirrer to increase the internal energy. As we discussed in the previous paragraph, the work done by (or on) the moving piston is  $-\int PdV$ . Thus the energy balance becomes

$$(\Delta U)_2 = -\int P_2 dV_2 \quad (52)$$

In these experiments, if  $dV_2$  is zero, it follows that  $\Delta U_2$  is zero. From Eq. (28), however, when  $dV_1$  is zero, we have

$$(\Delta U)_1 = -\int T_1 dS_1 \quad (53)$$

It seems then, that whatever  $S$  represents is constant during the experiments we are considering, since  $(\Delta U)_1$  must be zero as long as  $V$  is constant. Thus we have, for these experiments,

$$(\Delta U)_1 = -\int P_1 dV_1 \quad (54)$$

Since we have equated the  $U$  and the  $V$  terms, Eqs. (52) and (54) will only yield the required results for all possible experiments if the  $P$  terms represent the same quantity. We thus identify the variable  $P$  which we defined in Eq. (16) by  $P = -U^{SV}$  with our physical concept of *pressure*.

It then follows that we may put

$$w = W = -\int PdV \quad (55)$$

and hence

$$q = Q = \int TdS \quad (56)$$

If the process is not at equilibrium at each stage (that is, it is not a reversible process), then  $w \neq -\int PdV$ . Thus for this type of process,  $w \neq W$  and so  $q \neq Q$ . In practice, we seem to find that

$$w \geq W = -\int PdV \quad (57)$$

so that

$$q \leq Q = \int TdS \quad (58)$$

### Predicting the Behavior of a System

Figure 3 shows an example of what we may regard as the basic problem of thermodynamics; if we can find a method for solving problems of this nature, we shall in fact be well on the way to our desired objectives. The diagram shows a container constructed of walls which are

- **rigid** so that the volume of the material which they contain cannot change
- **adiabatic** so that the transfer of energy to the contents of the container by the " $q$ " process is not possible
- **impermeable** so that the material in the container cannot penetrate the walls, nor can additional matter enter through the walls

The container is divided into two sections by a barrier, the material of which is also rigid, adiabatic, and impermeable. The volumes on each side of the divider contain material at specified conditions (nature of the matter, amount of matter, temperature, pressure, etc.). These conditions need not be the same for each side.

We assume that each side of the apparatus is in an *equilibrium state*, by which we mean that there

are no observable macroscopic changes in the state of the matter in the system with time ("observable" using whatever senses or methods of measurement we might apply.) We shall further assume that we are concerned with *simple systems*, which are chemically inert and homogeneous.

The problem which we wish to solve is this: Suppose that one (or more) of the constraints imposed by the barrier is removed. If we remove the rigidity constraint, for example, we allow the barrier to move. Removing the adiabatic constraint permits energy to transfer as  $q$  through the barrier while maintaining the other constraints. Removing the impermeability constraint would permit material to pass through the barrier, which would still be rigid and adiabatic. (It is less easy to think of how this might be achieved directly in practice, but that is no reason for not considering the problem.) When any of the constraints are removed, we can see that in general some (at least) of the conditions in the two sections of the apparatus will change. We wish to predict the new equilibrium states that will result.

We know from experiments that if we release the constraints, certain things will happen, but not the reverse. For example, pressure, temperature, and concentrations tend to equalize, while the reverse does not happen. These statements in no way violate anything we have said before, but neither do they give us any information as to which states the system will proceed to at equilibrium. In order to describe these experiments it is necessary to have further postulates. Furthermore, while we have agreed that we have some idea of what constitutes a constant  $S$  experiment, we have not really defined either  $S$  or  $T$ . Thus, what follows addresses the definition of these quantities, and gives us results which are in accordance with our knowledge of the real world.

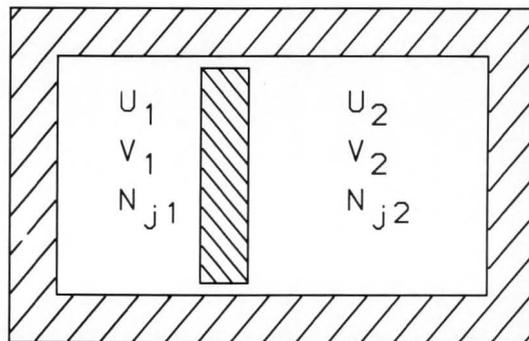


FIGURE 3. Apparatus with internal partition.

### Solving the Problem: The Postulates

We shall accept that matter contained in a system in an equilibrium state has an internal energy  $U$ , and that this is an extensive property (so that it is proportional to the amount of material present) and an additive property (so that the total internal energy of the apparatus is the sum of the internal energy of the two portions). We shall then make our first postulate:

**POSTULATE 1:** Equilibrium states are completely characterized by the values of  $U$ ,  $V$ , and  $N_j$ —that is, by their internal energy, volume, and number of moles of various materials which they contain.

Note that this is entirely consistent with our experimental knowledge that (for a fixed amount of a given substance) the equilibrium properties are a function of two variables. The two variables that are chosen are a pair which do not give rise to the problems with uniqueness discussed earlier.

We now consider how to predict the state to which our system will move when we relax (as discussed above) one of the internal constraints. Will it, for example, move to the state of lowest energy? This idea might sound attractive; unfortunately, a little further thought shows that the rigid, adiabatic nature of the external walls (which constraints are *not* going to be relaxed) means that both  $q$  and  $w$  will be zero. Hence  $\Delta U = q + w = 0$ ; that is, the total internal energy of the system is going to remain constant. Thus, this suggestion is not correct. We need some further postulates:

**POSTULATE 2:** Each equilibrium state of a simple system has a property  $S$ , to which we shall give the name *entropy*. This can be modeled mathematically by

$$S = S^{U,V,[N_j]}(U,V,[N_j]) \quad \text{where } S^{U,V,[N_j]} > 0 \quad (59)$$

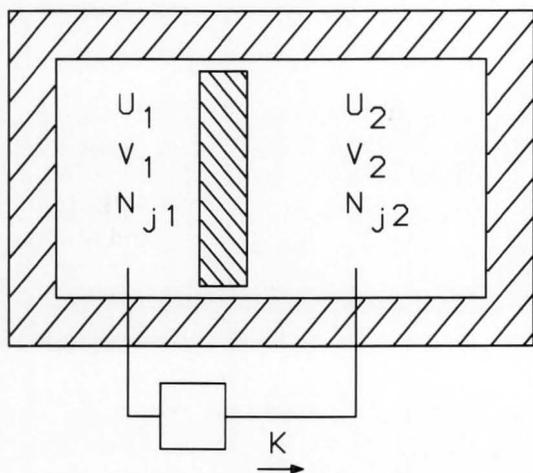


FIGURE 4. Alternative form of experiment.

**POSTULATE 3:** Entropy  $S$  is *extensive*. That is,  $S = N\hat{S}$ , and for a composite system of  $n$  equilibrium states of simple systems, the total entropy is additive; that is

$$S = \sum_{k=1}^n S_k \quad (60)$$

Now let us consider the apparatus of Figure 3. Suppose that we have the apparatus in an initial state, with the contents of the two sides at different conditions. The material in each side is in an equilibrium state. Suppose that for each side we know the function  $S = S^{U,V,N_j}$ . We may therefore calculate the entropies  $S_1$  and  $S_2$  of the two sides of the apparatus, and from Postulate 3, the total entropy, which is given by  $S_{\text{tot}} = S_1 + S_2$ .

We now relax the adiabatic constraint imposed on the internal partition. This means that energy may move (as  $q$ ) between the two sides of the apparatus. We want to be able to predict the conditions on each side of the partition when the apparatus reaches its new equilibrium state (we shall call this Experiment 1). The energy balance for either side of the apparatus is of the form  $\Delta U = q + w$ , but  $w = 0$  since the barrier is rigid ( $\Delta V = 0$ ). Thus after energy  $q$  has moved from one side to the other, the internal energies will be  $U_1 - q$  and  $U_2 + q$ , respectively.  $V_1$ ,  $V_2$ ,  $N_{1j}$ , and  $N_{2j}$  remain unchanged. We may therefore calculate new values for  $S_1$ ,  $S_2$ , and  $S_{\text{tot}}$ .

Consider now the alternative form of the experiment shown in Figure 4 (which we shall call Experiment 2). Here the adiabatic nature of the partition is maintained, but some form of "energy exchange machine" removes energy  $k$  from side 1 and adds the same quantity of energy to side 2. Again, we may calculate the total entropy  $S_{\text{tot}}^k$ , which by Postulate 3 equals  $S_1 + S_2$  for any value  $k$  of the energy transferred.

We now postulate that the equilibrium state that will be reached in Experiment 1 is the same as the state of Experiment 2, at which  $S_{\text{tot}}^k$  has its maximum value. Notice that at each stage of Experiment 2, after transferring energy  $k$ , we have to wait for the two parts of the apparatus to reach equilibrium states before we can calculate  $S_1$  and  $S_2$ , since Postulates 1 and 2 both apply only to equilibrium states. It would therefore be wrong to say that in Experiment 1 conditions change so that  $S$  goes to a maximum. While conditions in the apparatus are changing, it is obviously not in an equilibrium state, and  $S$  is not defined. We therefore state our new postulate as follows:

**POSTULATE 4:** The equilibrium state resulting after the removal of an internal constraint is that possible constrained state with maximum entropy. (We assume that there is only one such constrained maximum.)

Let us now apply the theory we have stated to the solution of the problem of Experiments 1 and 2. We have

$$dU = TdS - PdV + \sum \mu_i dN_i \quad (61)$$

If we consider only small values of the differentials  $dU$ ,  $dS$ ,  $dV$ , and  $dN_i$ , then these small values on the tangent plane will correspond to small changes in the physical system. (If the changes are not small, the values of the [derivatives]  $T$ ,  $P$ , and  $\mu_i$  of the real system will change, so that the differentials [which all lie on the tangent plane at a particular point] no longer represent possible states of the real system.) Identifying these small values by the symbol  $\delta$ , we may write

$$\delta U = T\delta S - P\delta V + \sum \mu_i \delta N_i \quad (62)$$

Since the partition retains its rigid and impermeable nature, we know that

$$\delta V_1 = \delta V_2 = 0 \quad (63)$$

and

$$\delta N_{1j} = \delta N_{2j} = 0 \quad (64)$$

Thus

$$\delta U_1 = T_1 \delta S_1 \quad \text{and} \quad \delta U_2 = T_2 \delta S_2 \quad (65)$$

or

$$\delta S_1 = \frac{1}{T_1} \delta U_1 \quad \text{and} \quad \delta S_2 = \frac{1}{T_2} \delta U_2 \quad (66)$$

Now

$$\delta S_{\text{tot}} = \delta S_1 + \delta S_2 \quad (67)$$

$$= \frac{1}{T_1} \delta U_1 + \frac{1}{T_2} \delta U_2 \quad (68)$$

For the whole apparatus, the energy is the sum of that in the two portions; hence

$$U_{\text{tot}} = U_1 + U_2 \quad (69)$$

Since the exterior walls are rigid, impermeable, and adiabatic, the total energy of the apparatus is constant ( $q = w = 0$ ), *i.e.*,

$$\delta U_{\text{tot}} = \delta U_1 + \delta U_2 = 0 \quad (70)$$

Hence

$$\delta U_1 = -\delta U_2 \quad (71)$$

Thus

$$\delta S_{\text{tot}} = \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \delta U_1 \quad (72)$$

From which

$$\frac{\partial S_{\text{tot}}^{U_1}}{\partial U_1} = \frac{1}{T_1} - \frac{1}{T_2} \quad (73)$$

Equation (73) follows from Eq. (9); although the  $\delta$  values are small, they are still differentials, since they came from Eq. (61).

For a maximum of  $S^{U_1}$ , this derivative will be zero. Thus, Postulate 4 tells us that at the new equilibrium state we will have

$$\frac{1}{T_1} - \frac{1}{T_2} = 0 \quad \text{or} \quad T_1 = T_2 \quad (74)$$

### Temperature

We may also consider what happens if we do not allow the system to go all the way to this final equilibrium state; that is, if we relax the adiabatic constraint on the barrier for only a short time and then reimpose it. This is the same as operating the apparatus in Figure 4, but using the energy-transfer machine to transfer a lesser amount of energy than would maximize  $S$ .

Suppose that the initial state of the system is such that when we relax the adiabatic constraint on the internal partition, energy moves as heat from compartment 1 into compartment 2. It follows that  $U_1$  will decrease (and  $U_2$  will increase by the same amount). These changes in  $U_1$  and  $U_2$  will cause a change in  $S_{\text{tot}}$  (as in Eq. 68) which must be positive, since  $S$  must change towards its maximum. Consider the graph of  $S_{\text{tot}}$  versus  $U_1$ , as shown in Figure 5. Since we have  $\Delta U_1 < 0$  and  $\Delta S_{\text{tot}} > 0$ , we have moved from a point such as A towards a point such as B, and along this curve

$$\frac{\partial S_{\text{tot}}^{U_1}}{\partial U_1} < 0 \quad (75)$$

thus

$$\frac{1}{T_1} - \frac{1}{T_2} < 0 \quad \text{or} \quad T_1 > T_2 \quad (76)$$

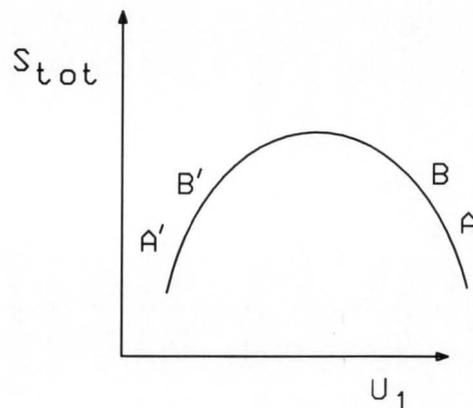


FIGURE 5. Maximum of  $S^{U_1}$

By a similar argument, we can see that if the heat flow is from compartment 2 to compartment 1,  $\Delta U_1$  will be positive, and we will be moving from a point such as A' towards B'. Thus the derivative of Eq. (75) will be positive, and we will conclude that  $T_1 < T_2$ .

Finally, we note that in Eq. (16) (or Eq. 75) we defined T by

$$T = U^{S'V} \quad (16)$$

which is exactly equivalent to the definition

$$T = \hat{U}^{\hat{S}'\hat{V}} \quad (77)$$

It follows that T is *intensive*, i.e., independent of the amount of material we are considering.

We thus have for the quantity represented by our symbol T that

- it is intensive
- at equilibrium, in the absence of any adiabatic constraint, we find that  $T_1 = T_2$
- prior to equilibrium, q moves from 1 to 2 when  $T_1 > T_2$  and from 2 to 1 when  $T_1 < T_2$

We thus see that T fulfills all our intuitive notions of the concept of *temperature*, and we shall in the future identify T with temperature. We may further note that it was part of Postulate 2 that

$$S^{U'VN_j} > 0$$

hence

$$U^{S'VN_j} = \frac{1}{S^{U'VN_j}} > 0 \quad (78a)$$

i.e.,

$$T > 0 \quad (78b)$$

### Equations of State

Postulate 2 (Eq. 59) tells us that we may write the entropy of a simple system in an equilibrium state as a function of the internal energy U, the volume V, and the number of moles of various materials:

$$S = S^{U,V,N_j} \quad (59)$$

Now recall the definitions of T and P

$$T = U^{S'V} = T^{SV} \quad (18)$$

and

$$P = -U^{SV'} = P^{SV} \quad (16)$$

We may substitute for S in these equations from Eq. (59) and then eliminate S between the resulting equations to obtain a relationship between V, T, P, and  $N_j$ . As an example, suppose that for a particular

system

$$S = K(NVU)^{1/3} \quad (79)$$

where N is the total number of moles involved. From this expression

$$T = \frac{\partial U^{SV}}{\partial S} = \frac{3S^2}{NVK^3} \quad (80)$$

and

$$P = -\frac{\partial U^{SV}}{\partial V} = \frac{S^3}{NV^2K^3} \quad (81)$$

from which

$$P^2V = \frac{N}{27} T^3 K^3 \quad (82)$$

These relationships between P, V, T, and N are the form of equation of state to which we are accustomed in physics and chemistry. Notice that, unfortunately, it is not in general possible to reconstruct Eq. (79) or its equivalent from Eq. (82), the equation of state, without further information. From Eq. (82) we have

$$\left(\frac{\partial U^{SV}}{\partial V}\right)^2 V = \frac{NK^3}{27} \left(\frac{\partial U^{SV}}{\partial S}\right)^3 \quad (83)$$

and we cannot obtain a solution to this partial differential equation without boundary conditions.

### Units and Value for Temperature

If we consider our definition  $T = U^{SV}$ , we see that the units and value of T will depend upon those which we ascribe to S. Working in the other direction, we may choose to give T arbitrary units of degrees Kelvin. Since U must have energy units, this means that we are assuming units of J/K for S, or J/mol K for  $\hat{S}$ .

For historical reasons, we are probably stuck with this system. If we were free to start from scratch it might be more logical to let  $\hat{S}$  be dimensionless, which would result in measuring temperature in Joules per mole. In particular, it would be possible to choose a temperature scale such that the ubiquitous "gas constant"  $R = 8,314$  J/mol K (and many other possible equivalent values) had a dimensionless value of 1. The time saved by chemists and chemical engineers in units conversions involving R would surely be enormous!

### Other Versions of the Problem

We have considered only one version of the problem posed above. The reader should be able to provide the solution to other versions and show, for example, that

- relaxation of the rigidity constraint on the partition leads to a final equilibrium state in which the pressures in the two compartments are equal

- removal of both the adiabatic and rigidity constraints results in a final equilibrium state in which both the temperatures and the pressures in the two compartments are equal
- removal of the adiabatic and impermeability constraints gives a final equilibrium state in which the temperatures are equal and  $\mu_{i1} = \mu_{i2}$  for all  $i$ .

We may regard  $T$  as a "thermal potential," in that a difference in  $T$  tends (in the absence of constraints) to cause energy to transfer as  $q$ . Similarly,  $P$  is a "mechanical potential," tending to cause work to be done (as an  $\int PdV$  term). In the light of the third result above, we name  $\mu$  the *chemical potential*, since a difference in  $\mu_i$  produces a potential for the movement of component  $i$ .

We note that in this approach it is not necessary to "define"  $S$  by way of equations such as  $\delta S = \delta q/T$ , where the value of  $\delta q$  is so circumscribed that the equation really has no meaning, and the student ends up learning the subject (if at all) by a hierarchical process of learning what is or is not permissible. The difficulty of trying to understand the "meaning" of entropy is obviated by having a perfectly formal way of defining it. Thus we only need to calculate its value, not to understand it.

## ACKNOWLEDGEMENTS

The two parts of this paper lean heavily on the approach of our former colleague, W. F. Harris. He introduced the thermodynamics course in this form at our university, but unfortunately his interests turned elsewhere before he could produce the definitive write-up we were always promised. It is therefore true to say that the felicities of the approach are his, and any faults in the detailed development are ours. □

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## REVIEW: Introduction to Rheology

*Continued from page 131.*

phenomena, to material functions, and to the importance of rheology in industrial processes. The text is complemented by numerous tables and figures that illustrate the behavior of a wide range of materials. Theoretical and empirical relationships among material functions are discussed in these chapters, and well-known models for non-Newtonian viscosity (*e.g.*, power law, Carreau, Bingham) and for linear viscoelasticity (*e.g.*, Kelvin, Maxwell, Jeffreys) are presented.

Each of the chapters mentioned above includes a

section describing the experimental measurement of the material functions discussed in the chapter. This emphasis on rheometry will be interesting and useful to many readers, especially those involved with rheological characterization of materials. Measurement techniques and configurations of commercial rheometers and research instruments are surveyed, and the suitability of particular types of instruments for particular tasks is discussed. Theoretical principles of measurements in various rheometer geometries are presented, and excellent introductory discussions of the factors limiting the range and accuracy of measurements are provided.

While the first part of the book is concerned with general aspects of rheology, the sixth and seventh chapters are devoted, respectively, to the rheology of polymeric liquids and the rheology of suspensions. These chapters provide an overview of two important areas of rheology, and also include introductions to topics of current research interest such as liquid crystal polymers, reptation models, and numerical simulations of suspension rheology.

The final chapter returns to continuum mechanics, a topic no doubt dreaded by many of the intended readers. But those who persevere are rewarded by a concise statement, mostly in words rather than equations, of the principles of continuum mechanics that govern the formulation of constitutive equations. A highly condensed survey of the mathematical forms and rheological predictions of constitutive models is also included. This brief chapter refers interested readers to many excellent references for more detailed treatments of the subject.

Throughout the book, the authors guide the reader toward more comprehensive sources of information, and the reference list is excellent and up-to-date. Although the treatment of many topics is necessarily brief, it is authoritative, and beginning rheologists will not need to relearn the material as they advance in their sophistication. The text is well written, and it is infused with explanations of the history and development of rheology, which enhance the reader's pleasure as well as his or her understanding. The book is very suitable as a textbook for an introductory course in rheology. However, the material is not presented in a problem-oriented style, and some instructors may feel that the absence of example and homework problems is a drawback. The book is certainly well suited for individual study, and I would recommend it highly to anyone seeking a sound, but accessible, introduction to rheology. □

## ***AUTHOR GUIDELINES***

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**ACKNOWLEDGMENT** • Include in acknowledgment only such credits as are essential

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