



Morton M. Denn

of the University of California, Berkeley



articles on . . .

- ◆ Undergraduate Academic Advising (page 156)
Michael L. Mavrovouniotis
- ◆ Mathematica in the ChE Curriculum (page 136)
John R. Dorgan, J. Thomas McKinnon
- ◆ Random Thoughts: Speaking of Everything (page 130)
Richard M. Felder
- ◆ International Engineering Internship Program (page 126)
John M. Grandin, Kristen L. Verduchi
- ◆ Design Competition for Second-Year Students (page 102)
W. A. Davies
- ◆ Dynamic and Steady-State Behavior of a CSTR (page 132)
Aziz M. Abu-Khalaf
- ◆ Low-Cost Experiments in Mass Transfer: Part 2 (page 142)
I. Nirdosh, M.H.I. Baird
- ◆ CESL: The Chemical Engineering Simulation Laboratory (page 114)
Kofke, Grosso, Gollapudi, Lund
- ◆ The Mass Transfer Boundary Layer with Finite Transfer Rate (page 94)
Morton M. Denn
- ◆ Current Trends in Chemical Reaction Engineering Education (page 146)
Shalabi, Al-Saleh, Beltramini, Al-Harbi
- ◆ Applied Statistics: Are ChE Educators Meeting the Challenge? (page 122)
Roger E. Eckert
- ◆ Chemical Engineering Education in Turkey and the United States (page 150)
J. Richard Elliott, Jr.
- ◆ A Laboratory Experiment that Enhances Environmental Awareness (page 98)
Ken K. Robinson, Joshua S. Dranoff
- ◆ Demonstrations to Complement a Course in General Engineering Thermodynamics (page 108)
Douglas J. Dudgeon, J.W. Rogers, Jr.

ASEE
Annual
Meeting
ChE Division
Program
Page
120

and chemical engineering at the . . .

University of Washington

ACKNOWLEDGEMENT

DEPARTMENTAL SPONSORS

The following 159 departments contribute to the support of *CEE* with bulk subscriptions.

*If your department is not a contributor, write to
CHEMICAL ENGINEERING EDUCATION,
c/o Chemical Engineering Department • University of Florida • Gainesville, FL 32611-6005
for information on bulk subscriptions*

University of Akron	University of Kentucky	Princeton University
University of Alabama	Lafayette College	Purdue University
University of Alberta	Lakehead University	Queen's University
University of Arizona	Lamar University	Rensselaer Polytechnic Institute
Arizona State University	Laval University	University of Rhode Island
University of Arkansas	Lehigh University	Rice University
Auburn University	Loughborough University	University of Rochester
Ben Gurion University of the Negev	Louisiana State University	Rose-Hulman Institute of Technology
Brigham Young University	Louisiana Technical University	Rowan College
University of British Columbia	University of Louisville	Rutgers, The State University
Brown University	University of Maine	San Jose State University
Bucknell University	Manhattan College	University of Saskatchewan
University of Calgary	University of Maryland	University of Sherbrooke
University of California, Berkeley	University of Maryland, Baltimore County	University of South Alabama
University of California, Davis	University of Massachusetts	University of South Carolina
University of California, Irvine	University of Massachusetts, Lowell	South Dakota School of Mines
University of California, San Diego	Massachusetts Institute of Technology	University of South Florida
University of California, Santa Barbara	McGill University	University of Southern California
California Institute of Technology	McMaster University	University of Southwestern Louisiana
California State Polytechnic Institute	McNeese State University	State University of New York, Buffalo
California State University	University of Michigan	Stevens Institute of Technology
Carnegie-Mellon University	Michigan State University	University of Sydney
Case Western Reserve University	Michigan Technical University	Syracuse University
University of Cincinnati	University of Minnesota	Technion-Israel Institute of Technology
Clarkson University	University of Minnesota, Duluth	University of Tennessee
Clemson University	University of Mississippi	Tennessee Technological University
Cleveland State University	Mississippi State University	University of Texas
University of Colorado	University of Missouri, Columbia	Texas A & M University, College Station
Colorado School of Mines	University of Missouri, Rolla	Texas Tech University
Colorado State University	Montana State University	University of Toledo
Columbia University	University of Nebraska	Tri-State University
University of Connecticut	University of New Hampshire	Tufts University
Cornell University	University of New Haven	University of Tulsa
Dartmouth College	New Jersey Institute of Technology	Tuskegee Institute
University of Dayton	University of New Mexico	University of Utah
University of Delaware	New Mexico State University	Vanderbilt University
Drexel University	North Carolina A & T University	Villanova University
University of Edinburgh	North Carolina State University	University of Virginia
University of Florida	University of North Dakota	Virginia Polytechnic Institute
Florida Institute of Technology	Northeastern University	University of Washington
Florida State/Florida A&M University	Northwestern University	Washington State University
Georgia Institute of Technology	University of Notre Dame	Washington University
University of Houston	Technical University of Nova Scotia	University of Waterloo
Howard University	Ohio State University	Wayne State University
University of Idaho	Ohio University	West Virginia Graduate College
University of Illinois, Chicago	University of Oklahoma	West Virginia Institute of Technology
University of Illinois, Urbana	Oklahoma State University	West Virginia University
Illinois Institute of Technology	Oregon State University	Widener University
University of Iowa	University of Ottawa	University of Wisconsin
Iowa State University	University of Pennsylvania	Worcester Polytechnic Institute
Johns Hopkins University	Pennsylvania State University	University of Wyoming
University of Kansas	University of Pittsburgh	Yale University
Kansas State University	Polytechnic Institute of New York	Youngstown State University

EDITORIAL AND BUSINESS ADDRESS:

Chemical Engineering Education
 Department of Chemical Engineering
 University of Florida • Gainesville, FL 32611
 PHONE and FAX : 352-392-0861
 e-mail: *cee@che.ufl.edu*

EDITOR

T. J. Anderson

ASSOCIATE EDITOR

Phillip C. Wankat

CONSULTING EDITOR

Mack Tyner

MANAGING EDITOR

Carole Yocum

PROBLEM EDITORS

James O. Wilkes and Mark A. Burns
 University of Michigan

LEARNING IN INDUSTRY EDITOR

William J. Koros
 University of Texas, Austin

PUBLICATIONS BOARD**• CHAIRMAN •**

E. Dendy Sloan, Jr.
 Colorado School of Mines

• PAST CHAIRMEN •

Gary Poehlein
 Georgia Institute of Technology

Klaus Timmerhaus
 University of Colorado

• MEMBERS •

Anthony T. DiBenedetto
 University of Connecticut

Thomas F. Edgar
 University of Texas at Austin

Richard M. Felder
 North Carolina State University

Bruce A. Finlayson
 University of Washington

H. Scott Fogler
 University of Michigan

Angelo J. Perna
 New Jersey Institute of Technology

Stanley I Sandler
 University of Delaware

Richard C. Seagrave
 Iowa State University

M. Sami Selim
 Colorado School of Mines

James E. Stice
 University of Texas at Austin

Donald R. Woods
 McMaster University

Chemical Engineering Education**Volume 30****Number 2****Spring 1996****► DEPARTMENT**

82 University of Washington, *Eric M. Stuve*

► EDUCATOR

88 Morton M. Denn, *Arup K. Chakraborty,*
Arthur B. Metzner, T.W. Fraser Russell

► CLASSROOM

- 94 The Mass Transfer Boundary Layer with Finite Transfer Rate,
Morton M. Denn
- 102 Design Competition for Second-Year Students, *W. A. Davies*
- 108 Demonstrations to Complement a Course in General Engineering
 Thermodynamics, *Douglas J. Dudgeon, J.W. Rogers, Jr.*

► LABORATORY

- 98 A Laboratory Experiment that Enhances Environmental Awareness,
Ken K. Robinson, Joshua S. Dranoff
- 142 Low-Cost Experiments in Mass Transfer: Part 2,
I. Nirdosh, M.H.I. Baird

► COMPUTERS IN EDUCATION

114 CESL: The Chemical Engineering Simulation Laboratory,
David A. Kofke, Marc R. Grosso, Sreenivas Gollapudi, Carl R.F. Lund

► SURVEY

- 122 Applied Statistics: Are ChE Educators Meeting the Challenge?
Roger E. Eckert
- 146 Current Trends in Chemical Reaction Engineering Education,
Mazen Shalabi, Muhammad Al-Saleh, Jorge Beltramini, Dulaihan Al-Harbi

► LEARNING IN INDUSTRY

126 International Engineering Internship Program,
John M. Grandin, Kristen L. Verduchi

► RANDOM THOUGHTS

130 Speaking of Everything, *Richard M. Felder*

► CLASS AND HOME PROBLEMS

132 Dynamic and Steady-State Behavior of a CSTR, *Aziz M. Abu-Khalaf*

► CURRICULUM

- 136 Mathematica in the ChE Curriculum,
John R. Dorgan, J. Thomas McKinnon
- 150 Chemical Engineering Education in Turkey and the United States, *J. Richard Elliott, Jr.*

► ADVISING

156 Undergraduate Academic Advising, *Michael L. Mavrovouniotis*

► 145 ERRATUM

CHEMICAL ENGINEERING EDUCATION (ISSN 0009-2479) is published quarterly by the Chemical Engineering Division, American Society for Engineering Education, and is edited at the University of Florida. Correspondence regarding editorial matter, circulation, and changes of address should be sent to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL 32611-6005. Copyright © 1996 by the Chemical Engineering Division, American Society for Engineering Education. The statements and opinions expressed in this periodical are those of the writers and not necessarily those of the ChE Division, ASEE, which body assumes no responsibility for them. Defective copies replaced if notified within 120 days of publication. Write for information on subscription costs and for back copy costs and availability. POSTMASTER: Send address changes to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL 32611-6005.

UNIVERSITY OF WASHINGTON

ERIC M. STUVE

University of Washington • Seattle, WA 98195-1750

It was too early to exchange pleasantries; the ringing phone could only mean that something was wrong—at best a wrong number, at worst, well, who knows? Thus awakened on Saturday morning in February, 1964, Albert “Les” Babb quickly ruled out the first possibility. The easily recognizable voice belonged to Dr. Belding Scribner, inventor of the arteriovenous shunt, and he was obviously distressed. Scribner related that the “Who-Shall-Live Committee” had just denied treatment to a 16-year-old high school honor student and “[her] only hope for survival would be to get intermittent dialysis therapy within the next four months!”

Babb, a chemical engineering professor at the University of Washington, knew full well the binding and irrevocable nature of the committee’s decision and its consequences for the patient, the daughter of a friend of his. He had just overseen development of the “monster,” a multi-patient dialysis machine in use at the University of Washington hospital.

After Scribner’s call, Babb’s next course of action was clear; he must develop an in-home dialysis machine that could be used without medical supervision and he must do so within the next four months. Scribner and Babb quickly assembled a team of physicians and engineers, and the “Mini-I,” the first in-home portable dialysis machine, made its lifesaving debut in June of that year. Commercial production of dialysis machines based on the Mini-I and its novel continuous proportioning dialysate system began the following year, and by 1969 the system was the predominant method of dialysis. Today it is the exclusive method.

The portable dialysis machine is one of the many treasured accomplishments of our Department of Chemical Engineering. Accredited by the AIChE in 1926 (only the second year in which accreditation was offered) the department has a long history leading up to its current position as a flourishing institution of research and

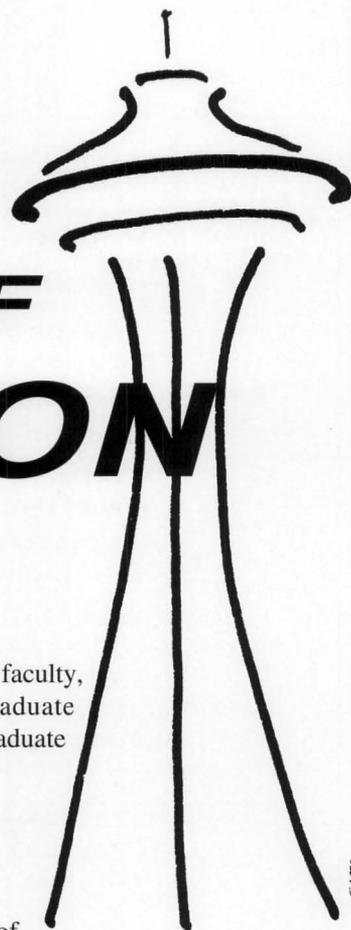
teaching with 14 full-time faculty, 10 staff members, 60 graduate students, and 150 undergraduate students.

THE UNIVERSITY OF WASHINGTON AND SEATTLE

The 680-acre University of Washington (UW) campus blends woodlands, wetlands, landscaped verandas, and urban architecture into a setting of uncommon beauty. The main campus sits on a predominantly southward-facing, and sometimes steep, slope etched out by glaciers during the ice age. Two of the many visual highlights of the campus include the “Quad,” with its breathtaking display of blooming Japanese Cherry trees each spring, and the Rainier Vista, the main promenade that makes a virtual connection between the campus and the 14,400-ft peak of Mt. Rainier a hundred miles to the southeast. Within this setting, 25,000 undergraduate students, 9,000 graduate and professional students, and 2,800 faculty carry out the pursuit of education and scholarship.

The campus is located just four miles northeast of downtown Seattle, where the University began as the Territorial University in 1861. It remained there until 1893, when it moved “as far away from the city as is reasonable” to its present location.

Seattle has prospered as a center of transportation—water, rail, air, and even bicycle. In *Cry of the Wolf*, Jack London describes Seattle’s role as the starting point in the Alaskan-Yukon gold rush of 1898-99. It also became the western terminus of the Great Northern railroad from Minneapolis-St. Paul in 1893—under the ownership and control of the “empire builder,” James J. Hill, it was the first transcontinental railroad built without government subsidy. Three statues stand on the UW campus today: one, naturally, is of



George Washington; another is of the composer Edward Grieg; and the third, J.J. Hill.

In 1916, lumberman William E. Boeing began building seaplanes to improve transportation throughout the vast Pacific Coastal waterways of the Northwest, and late in the 1920s, he formed a regional airline, both as a market for his planes and to deliver mail across the Cascade Mountains. In the early 50s it took "betting the company" to build the Boeing 707, the first successful commercial jet, establishing Boeing's place as the preeminent builder of commercial airliners. What about the airline? In 1934 the Roosevelt administration forced Boeing to divest itself of the airline—it is now United Airlines.

The newest chapter in transportation involves the bicycle. A vast network of bicycle trails threads through Seattle and neighboring areas, with the most prominent being the 17-mile Burke-Gilman trail, which runs through the campus along the right-of-way of an abandoned railroad. Chemical engineering students, staff, and faculty all use the trail for commuting, not just by bicycle but also by skateboard, roller blades, roller skis, and, of course, by foot!

THE CHEMICAL ENGINEERING DEPARTMENT

Chemical engineering began in 1904 as a discipline within the chemistry department. Its first BS degree was granted in 1907, and one of its first PhDs went to Waldo L. Semon in 1924 —Semon, now installed in the Inventor's Hall of Fame, first synthesized polyvinyl chloride; among his many other inventions, bubble gum remains the favorite of his grandchildren.

Henry K. Benson began teaching in 1905, specializing in industrial and physical chemistry and placing special emphasis on continuous (as opposed to batch) processing. At the end of World War I, he became Executive Officer of the new Department of Chemistry and Chemical Engineering. Subsequently, Prof. Beuschlein was hired to take on chemi-

cal engineering matters as Benson's responsibilities were set mostly by the much larger chemistry program.

Throughout the next two decades, chemical engineering continued in the hands of Benson and Beuschlein, and then in 1947 two relative newcomers, R. Wells Moulton, a PhD graduate of UW, and Joseph L. McCarthy, a former UW student with a PhD from

McGill, took the reins: Moulton took over Beuschlein's responsibilities of running the chemical engineering program, while McCarthy worked on cleaning up the polluted effluents of the local pulp mills.

In 1953, the Department of Chemical Engineering became established as a separate department within the College of Engineering, but remained physically with the Department of Chemistry in Bagley Hall. Moulton became chairman of the new department and oversaw a period of dynamic growth. He encouraged Les Babb to pursue the new field of nuclear engineering

and brought Babb and Scribner together for their collaboration leading to the Monster and Mini-I dialysis machines. Chemistry, chemical engineering, and the nuclear engineering group all expanded rapidly within Bagley Hall, and the time eventually came when additional space was needed. In 1967 chemical and nuclear engineering (with Babb as its chair) moved into their new home, Benson Hall—named after the founder of chemical engineering at UW.

Charles Sleicher became the next chairman in 1977 and continued the tradition of growth started by Moulton, establishing a center for surface science in 1983. The department's investment in new faculty also returned high dividends in the form of four PYI awards among a faculty of twelve. Sleicher remained chairman until 1989 when Bruce Finlayson became only the fourth chairman in the department's long history.

Benson Hall sits amid a diverse collection of natural and



Rainier Vista, the main promenade of the campus, with the tower of the Administration Building, Drumheller Fountain, and Mt. Rainier in the background. (Photo by Davis Freeman)



Eric Stuve

Above: Flanked by twin 20,000 volt coupling devices, graduate student Tim Pinkerton adjusts tip alignment in the field ion microscope. At Right: One of the twenty-five Japanese Cherry trees in full bloom in the Quad.

architectural beauty. It has 20,000 square feet of research laboratory space and 5,300 square feet of teaching laboratories, including the laboratories of unit operations, computer and process control, colloid and surface science, and electrochemistry. Supporting facilities include a well-equipped machine shop, electronics shop, and a computer network of 75 Macintosh-based machines and three Vaxes.

UNDERGRADUATE INSTRUCTION

Over the past twenty years, an average of 62 BS degrees have been granted yearly by the department. Recent enrollment has been quite stable, with 57 BS degrees granted last year, of which 40% went to women. Participation of women in the program has increased from an average of 30% over the last five years to 48% for the most recently admitted class. The department maintains an active scholarship program, and approximately 20% of each undergraduate class receives either full or partial support of their education through chemical engineering scholarships.

Undergraduate students from UW enter the department at the end of their sophomore year, while students transferring from one of the community colleges or state-wide four-year universities enter at the beginning of their junior year. Typically, about 40% of each class is made up of transfer students. The average entering grade-point average is 3.43, with 30% of students having a GPA of 3.7 or higher.

Once in the department, students take the canonical mass and energy balance course. Process simulation with Aspen is an integral part of all required undergraduate courses, and Babb has the formidable task of introducing sophomores and juniors to Aspen. Many students have had little experience with spreadsheet programs and computer communications protocols, so Babb also undertakes to redress these deficiencies.



Mary Levin

From there, the students take traditional courses in transport processes (fluid mechanics, heat transfer, and mass transfer), reactor design, and process control. Homework problems and class projects include work in design and statistics. Students also take two quarters of unit operations laboratory where they receive their first exposure to independent problem formulation, working in groups, taking and statistically analyzing data, and preparing convincing written and oral reports. All experiments are open-ended, with only minimal guidance from instructors; students are allowed, and even encouraged, to learn from each other.

Process design is covered in two courses in the last two quarters of the senior year. The first course introduces students to engineering economics and gives them a first crack at a "conceptual design" of an entire process in about three weeks. This design is done on Aspen and reawakens students to the systems approach to engineering design—for many a rude awakening, indeed. In the capstone course, students work in groups of four to design an entire chemical process both at the conceptual stage, where equipment specifications float, and at the application stage, where optimization proceeds with fixed equipment parameters. Students then submit phone-book size reports detailing their designs and rationale.

A number of elective options are available to students along the way. The department offers "specialty options" in which students focus at least 9 credits of their advanced chemistry and engineering science electives into a particular

Over the past twenty years, an average of 62 BS degrees have been granted yearly by the department. Recent enrollment has been quite stable, with 57 BS degrees granted last year, of which 40% went to women. Participation of women in the program has increased from an average of 30% over the last five years to 48% for the most recently admitted class.



Eric Stueve

Graduate student Theresa Jurgens-Kowal examines sample alignment in the X-ray photoelectron spectrometer.

area: biotechnology; polymers, composites, colloids, and interfaces; electronic materials; computers applied to chemical engineering; environmental engineering; and nuclear chemical engineering. About 40% of students perform undergraduate research projects both to prepare for entry into the job market and for graduate school.

At graduation time, the most important problem looming for students is finding a job. To help increase their employment prospects, the department encourages students to take co-ops during their studies and offers a two-track curriculum so that, with careful planning, students can take a six month co-op without lengthening their time to degree. Currently, about 19% of students take co-ops.

The current employment situation looks good, especially because of the increase in semiconductor manufacturing in the Northwest. No single type of job is preeminent; students find employment in small local companies, waste remediation at the Hanford Nuclear Reservation, semiconductor manufacturing, and of course, the oil and chemical process industries.

GRADUATE INSTRUCTION AND RESEARCH

The department has about sixty graduate students, all engaged in research activities. During the past five years the department has graduated an average of 10-11 PhDs each year, making it fourteenth in annual production of PhD chemical engineers. Entering graduate students take courses in applied mathematics, thermodynamics, fluid mechanics, heat transfer, and reaction kinetics during their first two quarters.

Students earn entry into the PhD program upon successful

completion of a Preliminary Exam that embodies the goal of teaching students to "learn how to learn" by assessing their abilities in three areas: a knowledge-base of chemical engineering fundamentals, critical and analytical thinking skills, and research performance itself. Fundamentals of chemical engineering are probed in an oral examination, and critical and analytical skills are assessed through a written and oral critique of a current research paper assigned to the student by the faculty. Once these two parts have been successfully completed (at the end of the second quarter), students then choose a research advisor and begin their thesis research in earnest. About six months later, students take the last part of the Preliminary Exam, in which they present and defend their research to date and field related questions from the faculty.

CHEMICAL ENGINEERING RESEARCH

The nature of research spans the full spectrum from molecular-level fundamental research to applied research for end-use products. Some major research successes of the department include the home kidney dialysis machine (Babb) mentioned at the beginning of this article, textbooks on numerical mathematics for chemical engineering (Finlayson), polymer composites for airplane manufacture (Seferis), design of a Seattle Metro sewer project (1993) that has saved local taxpayers about \$10 million (Ricker), and development of a biocompatible, plasma deposited polymer (Ratner).

Research in the department has grown according to a strategy of developing strength in a number of critical research areas. Today, the department offers a variety of research programs in surface science, biotechnology, environmental studies, computers and process control, and materials (polymers and thin films). These five topics represent the subject matter of eighteen research groups, yet research methodologies can be broadly categorized (with a few exceptions) into three groups. Seven research groups engage in some form of surface science, six in biotechnology, and four in computer methods. Perhaps the most distinctive exception is the work on industrial teaming, which has been implemented in the Boeing 777 program.

The relatively large proportion of surface science work is perhaps surprising for a chemical engineering department. **John Berg** began the department's modern surface science era by studying liquid interfacial and colloidal phenomena. Today, Berg offers an industrial short course on surface and colloidal science with about 45 participants each year. Berg's current research focuses on improved

absorbents and de-inking of papers.

In 1983 a \$500,000 grant from the Shell Companies Foundation established a state-of-the-art surface analysis center based on X-ray photoelectron spectroscopy. **Buddy Ratner** combined this center with operating funds from the NIH and began to study surfaces of biological interest, especially the biocompatibility of polymers used in implants. Shortly thereafter, **Eric Stuve** started his program of electrochemical surface science that incorporates both solid/liquid and solid/gas surface science, including a system that does both. This work focuses on fundamentals of electrochemistry and mechanisms of fuel cell reactions.

The growth of both "wet" and "dry" surface science has been steady throughout the last ten years. In the former category, **Dan Schwartz** has established an electrochemical engineering program that, among other projects, has developed a method of Raman spectroscopy that images multicomponent electrodeposition of magnetic thin films in situ and in real time. Ratner has added scanning probe techniques (scanning tunneling microscopy and atomic force microscopy) for imaging biological surfaces under water. **Tom Horbett** studies the response of cells to polymer surfaces with respect to platelet activation and surface thrombogenicity by thermodynamic means (adsorption isotherms) and a new imaging system incorporating a mega-pixel, cooled CCD camera.

In the latter (dry) category, **Dave Castner** studies polymer-metal interactions with X-ray photoelectron spectroscopy and X-ray absorption methods, the latter at the National Synchrotron Light Source (Brookhaven). **Bill Rogers** uses a wide range of surface science techniques to study novel organometallic precursors for growth of boron nitride and aluminum nitride thin films.

With all of this surface science comes a thirst for instrumentation. For its major surface science equipment, the department has four X-ray photoelectron spectrometers, two secondary ion mass spectrometers (one of which is time-of-flight), three atomic resolution microscopes, and a field ion microscope. Nine ultrahigh vacuum chambers support this equipment, as well as other (minor) instruments such as mass spectrometers, electron diffraction optics, and Auger spectrometers.

The department also maintains strong research programs in biotechnology. Those with surface science components (Castner, Horbett, and Ratner) were mentioned above. Two programs involve research on bacteria. Mechanisms of protein production in the bacterium *E. Coli* and regulation of protein folding by chaperonins are studied by **François Baneyx**. Another class of bacteria, the methylotrophs, which



Biker professors at a local rally. From left to right: Larry Ricker, Barbara Krieger-Brockett, Dan Schwartz, Brad Holt, Eric Stuve, Bruce Finlayson, and Lew Wedgewood. (Photo by Eric Stuve.)

feed on methane or chlorinated C_1 hydrocarbons, are examined with respect to their potential in bioremediation and other biocatalytic reactions by **Mary Lidstrom**.

Materials related research includes the surface science work of Schwartz and Rogers, mentioned above, as well as a strong emphasis on polymers. The Polymer Composites Laboratory of **Jim Seferis** examines the influence of processing methods on polymer performance. This work has been incorporated into the new Boeing 777, which is the first commercial airliner to incorporate polymers in structural components. **Graham Allan** works with natural polymers (wood fibers) to precipitate inorganic pigments inside the fiber. This increases the fiber's opacity to allow reduced fiber content in paper. The flow properties of macromolecules are studied both experimentally and numerically by **Lew Wedgewood**. This work combines traditional rheological measurements with numerical analysis and has led to a new vorticity theory for non-Newtonian fluids.

The department's program on environmental studies includes studies of the behavior of aerosols and solid particulates in the atmosphere, marine bioremediation, and reaction engineering. **Jim Davis** studies gas/solid and gas/droplet interactions and reactions with the aid of the dynamic electrobalance, a device capable of isolating and suspending single particles or droplets of micrometer size. Absorption (or release) of pollutant gases can be followed by light scattering, mass spectroscopy, and Raman spectroscopy. **Barbara Krieger-Brockett** examines thermal reactions (combustion) of solids and then uses statistical models to predict gas evolution rates during these reactions. She also

TABLE 1
Chemical Engineering Faculty, University of Washington

G. Graham Allan (Professor of Forest Resources): fiber and polymer science
Albert L. Babb (Professor Emeritus): reactor engineering, bioengineering <ul style="list-style-type: none"> • Past chair, Committee on Future Nuclear Power Development (National Academy of Sciences) • National Academy of Engineers
François Baneyx (Asst. Professor): biotechnology, protein technology, biochemical engineering <ul style="list-style-type: none"> • NSF-CAREER award
John C. Berg (Rehnberg Professor): interfacial phenomena, surface and colloid science; <ul style="list-style-type: none"> • Co-Editor in Chief, <i>Adv. Colloid & Interf. Sci.</i>; Editorial Board, <i>Langmuir, J. Colloid & Interf. Sci., Colloids & Surfaces, J. Adhesion Sci. & Tech.</i> • UW Distinguished Teaching Award; Guggenheim Fellowship; Alpha Chi Sigma Award
David G. Castner (Research Assoc. Professor): polymer and metal-organic interfaces, catalytic materials <ul style="list-style-type: none"> • Society for Biomaterials (chair, surf. charact. & modification group); American Vacuum Society (past local chapter chair, applied surface science division); Assoc. Editor, <i>Plasmas & Polymers</i>
E. James Davis (Professor): colloid and aerosol physics and chemistry, electrokinetics, light scattering <ul style="list-style-type: none"> • Regional Editor, <i>Colloid & Polymer Sci.</i>; Assoc. Editor, <i>Aerosol Sci. & Tech.</i>; Editorial Board, <i>J. Aerosol Sci., J. Colloid & Interf. Sci.</i>; American Association for Aerosol Research (past treasurer, vice president) • Sinclair Award
Bruce A. Finlayson (Rehnberg Professor and Chair): modeling of chemical engineering problems <ul style="list-style-type: none"> • CACHE (past trustee); AIChE (past director, CAST division chair); National Research Council; Editorial Board, <i>Intl. J. Num. Methods in Fluids, Num. Heat Transfer, Num. Methods Part. Diff. Eqns., Chem. Engr. Educ.</i> • Walker Award; AIChE Fellow; National Academy of Engineers
Bradley R. Holt (Assoc. Professor): process design and control <ul style="list-style-type: none"> • NSF-PYI Award
Thomas A. Horbett (Professor of Bioengineering): proteins at interfaces, biomaterials, drug delivery <ul style="list-style-type: none"> • Clemson Award
Barbara B. Krieger-Brockett (Assoc. Professor): reaction engineering
Mary E. Lidstrom (Jungers Professor): biomolecular engineering, metabolic engineering <ul style="list-style-type: none"> • American Academy of Microbiology; Editorial Board, <i>J. Bacteriol., FEMS Microbiol. Rev., FEMS Microbiol. Ecol.</i> • NSF Faculty Award for Women
Buddy D. Ratner (Professor of Bioengineering): biomedical polymer surfaces and interfaces <ul style="list-style-type: none"> • Editor, <i>Plasmas & Polymers</i>; Assoc. Editor, <i>J. Biomed. Matls. Res.</i>; Editorial Board, <i>Surface Sci. Spectra, J. Biomats. Sci., Biomaterials, Biomed. Matls.</i> • Clemson Award; Perkin Elmer Award
N. Lawrence Ricker (Professor): process control and optimization
J.W. Rogers, Jr. (Professor): surface chemistry and engineering, applications to thin film deposition <ul style="list-style-type: none"> • American Vacuum Society (past national program chair, publications committee chair); Editorial Board, <i>J. Vacuum Sci. & Tech. B</i> • Battelle Professorship
Daniel T. Schwartz (Asst. Professor): electrochemical engineering <ul style="list-style-type: none"> • Electrochemical Society (chapter chair) • DOE Jr. Faculty Award; NSF-PYI Award; UW Outstanding Faculty Achievement
James C. Seferis (Boeing/Steiner Professor): polymers and their composites, manufacturing, teaming <ul style="list-style-type: none"> • Past chair, Gordon Conference • NSF-PYI Award; Humboldt Prize; National Academy of Athens; Metler Award
Eric M. Stuve (Professor): electrochemical surface science <ul style="list-style-type: none"> • American Vacuum Society (past chapter chair, past director, trustee); Co-chair, Gordon Conference • Humboldt Fellowship; NSF-PYI Award
Lewis E. Wedgewood (Asst. Professor): computational fluid mechanics, macromolecular fluid flow,
Teaching Faculty
Kermit Garlid (Professor Emeritus): past Chair of Nuclear Engineering
William J. Heideger (Professor Emeritus): Director of Engineering Advising Center
Gene L. Woodruff (Professor): Dean Emeritus of the Graduate School

uses statistical methods to chart and predict the effects of marine bioremediation in Puget Sound in collaboration with the Department of Oceanography.

The computer-intensive research programs include those of Finlayson, Holt, and Ricker. **Bruce Finlayson** continues to apply computer methods to solution of chemical engineering problems, work that has grown out of his three textbooks on the subject. Current work includes a model for blood solutes passing through the heart and skeletal muscles and a model for the swallowing process with the ultimate aim of improving the condition of the millions of people with swallowing problems. **Brad Holt** studies the use of nonlinear control algorithms and neural networks to implement robust controllers, and **Larry Ricker** uses model predictive control to develop algorithms for complex continuous and batch processes. The Metro sewer project previously mentioned consisted of a program to manage twenty-three flow controllers in the existing sewer system to handle storm water runoff without polluting local bodies of water.

FACULTY

The department is fortunate to have a faculty deeply committed to all aspects of academic life: teaching, research, and administration. A goodly number of major awards have been bestowed on the faculty, including two positions in the National Academy of Engineering (Babb, Finlayson) and five NSF young investigator awards (Seferis, Holt, Stuve, Schwartz, Baneyx). The department also has a strong commitment to service; many faculty hold major positions on editorial boards or within professional societies. Table 1 lists the departmental faculty along with their research interests, major awards, and service appointments.

ACKNOWLEDGMENTS

Our special thanks go to J. Ray Bowen, Dean of UW's College of Engineering, Joseph L. McCarthy, Dean Emeritus of the Graduate School, and to R. Wells Moulton and Charles A. Sleicher, both of whom served as chair of the Chemical Engineering Department. □

MORTON M. DENN

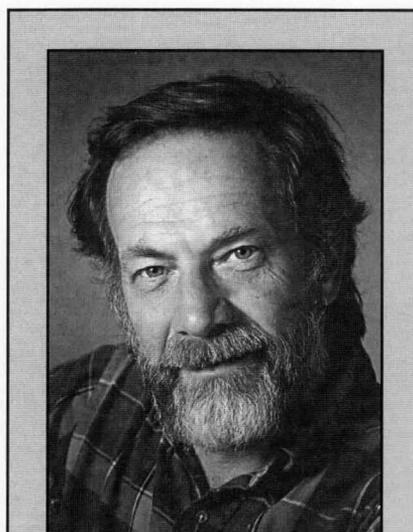
ARUP K. CHAKRABORTY,
ARTHUR B. METZNER,*
T.W. FRASER RUSSELL*
*University of California
Berkeley, CA 94720*

Morton Denn is a household name in modern chemical engineering circles, not only because of his many research accomplishments and service to our profession, but also because of the influence his books and classroom teaching have had on the education of young chemical engineers. In this paper, we, three of his former and current colleagues who span roughly three generations of chemical engineering academics, will highlight some of Mort's research accomplishments and provide perspective on some of his enduring contributions to chemical engineering education.

Mort was born and raised in Paterson (New Jersey), close to the city of New York. He got his first taste of "chemical engineering" in 1957 during a six-month stint as a laboratory assistant making foamed plastic boat bumpers and fishnet floats for the Linen Thread Company. This taste of chemical engineering served to whet Mort's appetite for the subject, and he later chose to major in chemical engineering at Princeton University.

An incident during his junior year at Princeton may have helped shape Mort's concise style of writing (it is difficult to find an extraneous phrase in articles and books written solely by Morton M. Denn). A laboratory report, graded by Michel Boudart, was returned to Mort liberally covered with red ink. He was humiliated that a native French speaker could find so much fault with his English and vowed that he would henceforth write in such a

* Address: University of Delaware, Newark, DE 19716



Now ▲

and . . .

then

(circa

1971),

sans

beard.



way that it would never happen again. Reading his textbooks and knowing of his exemplary work as editor of *AICHE Journal* and the *Journal of Rheology*, most would agree that he has succeeded.

Mort worked on his senior thesis with Bill Schowalter, a newly arrived Assistant Professor at the time. They aimed to carry out an experimental study of normal stresses in polymer solutions (people were still not convinced normal stresses were real in those days). Mort often remarks that after that experience it is a wonder that either of them ever did experiments again, despite the fact that *both* the data points were good ones. Meanwhile, he read tensor analysis and basic rheology papers with Schowalter and his students and developed a strong interest in the mathematical analysis of physical problems relevant to chemical engineers. This would be the underlying theme in much of Mort's early research and the pedagogy in his books.

Mort decided to pursue graduate studies in Minnesota. He was interested in mathematics in chemical engineering, and Richard Wilhelm had told him to go there. Also, in the summer of 1961, Mort had worked at the Dupont Engineering Research Laboratory in Wilmington with Alan Foss (later a faculty colleague at Berkeley), Jon Olson

(later a colleague at Delaware), Steve Whitaker, and the late Forest Mixon. These "experienced" coworkers told him that Rutherford Aris was the hot item in applied mathematics in chemical engineering, so Mort arrived in Minnesota with the goal of becoming an Aris student. As a result, Aris agreed to become the thesis advisor of yet another student who would later become one of the leaders of our profession.

Mort's thesis focused on optimization of systems with interconnecting structures, a problem that had been causing real difficulties but which proved to be "relatively straightforward" (Mort's view) when put into the proper format.

Just prior to completing his thesis, Mort learned from Schowalter (who was spending a sabbatical leave at Minnesota) that Metzner at Delaware was looking for a postdoctoral coworker in the area of non-Newtonian fluid mechanics. He applied for, and was offered, the job. At Delaware he continued to spend time working on optimization problems and explored a newfound interest in optimal control.

After one year as a postdoctoral scholar, Mort joined the faculty at the University of Delaware. Interestingly, he had a joint appointment: 75% in computer science and 25% in chemical engineering. Three years later he moved full time into chemical engineering since he found his interests and those of the computer science department were not moving in the same direction. Mort was also promoted to tenure in 1968 (in just three years!). Once, when he and Henry Weinberg were asked "How did you fellows get tenure so quickly in those days? Were you just so much better, or was it easier?" even before the irrepressible Weinberg could say anything, Mort replied without hesitation, "Both!"

What do we know about the young Mort Denn, and what fostered his ability to make incisive decisions with such apparent ease? Some insight may be gained through a story his father related at the annual AIChE meeting in 1977 when Mort received the Professional Progress Award. Mort had invited his parents to attend the ceremony, and when he was absent from the table for a few minutes, the conversation turned to the clarity with which Mort is able to analyze societal as well as professional issues and at what age these attributes may have developed. His father responded just as definitively as Mort usually does with the following story:

At a very early age. I remember an occasion when Morton had just passed his thirteenth birthday and General Eisenhower, running for election, scheduled a campaign appearance in our home town. By pressing the local Republican officials I was able to arrange for the General's motorcade to change its itinerary sufficiently to enable a brief stop at our store. I wanted our son to meet this famous hero of World War II—perhaps a once-in-a-lifetime opportunity. All was arranged; Morton came to the store at the appointed time, but was less than enthralled when I explained to him, for the first time, what I had in mind. The motorcade arrived and I stepped outside to meet

Morton Denn is a household name in modern chemical engineering circles, not only because of his many research accomplishments and service to our profession, but also because of the influence his books and classroom teaching have had on the education of young chemical engineers.

the general, but when he and I entered the store, Morton was nowhere to be found!. Clearly, he had taken full control of his own destiny by age thirteen and was ready to proceed incisively with developing it as he saw fit and with minimum outside interference.

The period from 1965 to 1977 was a remarkably productive period in Mort's career. He continued working on optimization of distributed parameter systems, and many of the papers he wrote during this period were among the first in that area. But his most insightful and lasting contributions were made in the field of rheology and non-Newtonian fluid mechanics. The following examples, taken from the broad range of problems that Mort worked on, make clear the impact of his research in the first dozen years of his career.

In 1970, Mort and one of his students, James Ultman addressed an issue that has since turned out to have deep implications for polymer flow and transport behavior.^[1] They were studying heat transfer from cylinders submerged in flowing polymer solutions. The experimental data of David James showed some rather unusual behavior, which they ascribed to the fact that the relevant transport equations changed from elliptic to hyperbolic (thus allowing discontinuities) when certain pertinent variables acquired values that exceeded a certain threshold. While the implementation was not done rigorously by Ultman and Denn, this idea has proved to be wide-ranging in its applicability to transport phenomena in polymeric liquids, and Dan Joseph and coworkers^[2] applied the idea rigorously to a variety of situations in the 1980s.

In 1971, Pino Marrucci and Mort published a paper on stretching of viscoelastic fluids that is characteristic of much of Mort's work in the first decade of his career— incisive, with profound implications, and yet mathematically simple. They analyzed the stretching of a rod of viscoelastic material.^[3] Marrucci was a former student of Gianni Astarita in Naples, and as we have noted earlier, Mort had started work on non-Newtonian fluids as Art Metzner's postdoc. Astarita and Metzner^[4] had published an analysis of some experiments based on the notion that the stress saturated as the stretching rate increased. Marrucci and Denn showed that this analysis was flawed, as it considered only the slow stretching rate asymptote; consideration of the fast stretching rate asymptote quickly showed the real physics. One can only imagine the pleasure the two youngsters derived from correcting their mentors' analysis. This paper with Marrucci, together with Mort's earlier work on boundary layers for elastic fluids, had an impact far beyond the difficulty of the

analysis because it led to deep physical insights. Both papers are widely cited and used as examples in textbooks.

In the late 1960s and early 1970s, Mort wrote a series of theo-



retical and experimental papers on Taylor-Couette instabilities in dilute polymer solutions^[5] that set the stage for a lot of subsequent work on flow stability. These papers emphasized, for perhaps the first time, the extreme sensitivity of certain flows to second-order rheological effects. Mort still regrets the fact that he missed the interesting case of the zero Reynolds number oscillatory instability that has been exploited extensively by Muller (now a Berkeley colleague), Larson, and Shaqfeh in the early 1990s.^[6] As he ruefully points out, the analysis for this case is there in his student Sun's thesis, but in a form that did not reveal the interesting physics.

The mid-70s marked the beginning of Mort's research on the simulation of polymer processing operations, especially melt spinning, where his work with students and collaborators has defined the state of the art. The spinning work spanned twenty years, starting with an unpublished MS thesis of Glen Zeichner (co-advised with Art Metzner and Byron Anshus), followed by a seminal 1975 paper with Petrie and Avenas,^[7] through a comprehensive book chapter^[8] to a very recent paper on dynamics and disturbance propagation.^[9] This period also marked the beginning of a productive collaborations with Jim Wei on the modeling of coal gasification reactors.

In addition to making seminal contributions to non-Newtonian fluid mechanics and stability, during this period Mort also wrote three of his five books. They cover a rather wide range of subjects: two are concerned with his stability and optimization interests, and one is a textbook for the first course in chemical engineering.^[10] Perhaps the most popular textbook that Mort has written is *Process Fluid Mechanics*,^[11] used in many chemical engineering departments around the world for undergraduate (and graduate) instruction.

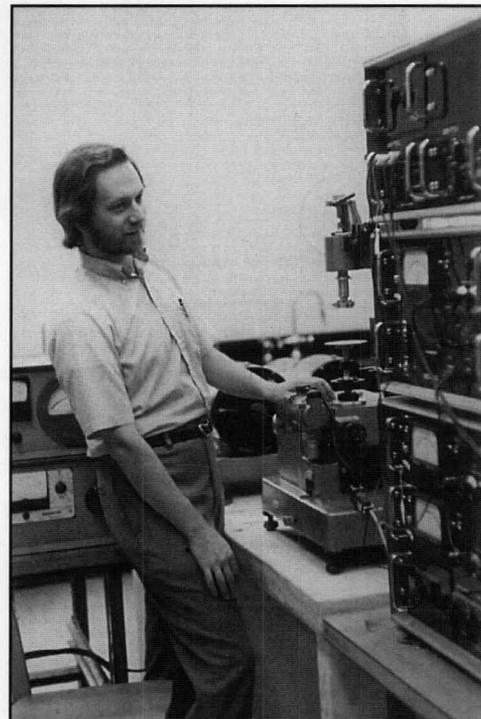
Starting in 1965, the Delaware chemical engineering department initiated a project to redesign the six-credit introductory sophomore courses in industrial stoichiometry. Mort and TWF Russell devoted six years of effort to this task, and the final product was a totally new approach to the traditional first course in chemical engineering. The history of this course's development (and the resulting textbook) was outlined in an issue of this journal over twenty-two years ago.^[12]

Some conclusions drawn by the authors that have stood the test of time and many years of classroom teaching by others are the "Denn-Russell rules":

- *Since chemical engineering departments require students to take freshman courses in mathematics, physics, and chemistry, it's incumbent upon them to use this material effectively in the introductory major course in chemical engineering.*

◀ **Mort and David Boger in the bush, late 1970s.**

Mort, circa 1972, at the University of Delaware: How do you operate a Weissenberg rheogonimeter with the plates six inches apart? ▼



- *A crucial part of chemical engineering is the design, planning, and interpretation of experiment, and this must be introduced early in the curriculum.*
- *To analyze experiments properly and to use the results for effective process or product design, it is essential that one be proficient in chemical engineering analysis. This is distinctly different from applied mathematics.*
- *There are two critical issues in chemical engineering analysis that must be effectively learned. The first is the ability to look at any physical situation and to develop the mathematical description; the second is the ability to compare model behavior with experiment and to draw conclusions.*
- *Students at the freshman or sophomore level have great difficulty obtaining the mathematical descriptions or model equations, and a key component of analysis is the presentation of logical procedures to obtain the correct equation.*



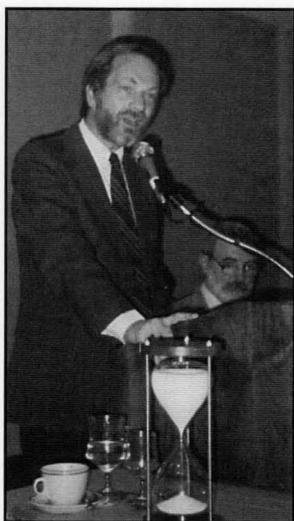
▲
Mort with Bob Bird and Bruce Finlayson on Ben Lomond during a break between morning and afternoon sessions at a 1981 conference.



▲
Mort and Jan Mewis, wine tasting at one of the area vineyards, 1981,

and

◀
in 1986, Mort accepts the Bingham Medal from the Society of Rheology.



- *To teach chemical engineering analysis effectively, one should begin with studies of liquid-phase reacting systems. With such systems, one can show students a direct relationship between laboratory experiment, mathematical modeling, and simple reactor and process design.*
- *In the context of teaching chemical engineering analysis, students must be introduced to rate of reaction and rate of mass transfer, the two cornerstones of chemical engineering.*
- *Analysis is a necessary, but not sufficient, skill for chemical engineers.*

Mort left a rich legacy of discussions with faculty, administrative officials, the Board of Trustees, and perhaps others, in Delaware. One concern was Mort's appointment as chairman of the newly instituted university-wide senate Committee on Promotions and Tenure. The new provost had decided that the University of Delaware could not really qualify for admission to the circle of respected research universities as long as faculty who were of indeterminate quality and motivation were promoted

to advanced status. Some departments had excellent criteria for promotion at that time, but others had rather slipshod criteria and procedures. The provost was anxious to see this ambivalence corrected, and the senate wisely chose Mort to carry the flag for this purpose. Mort denies the accuracy of the following recollection, but we do believe the salient points to be correct.

Evidently, in prior years (before the establishment of the senate committee) some department chairmen submitted rather informal and incomplete files directly to the administration in support of promotion requests, confident that in those days of rapid enrollment growth every warm body was sorely needed to meet teaching needs. One chairman, late to submit his document, had it carried to Mort's department where it was simply popped into the appropriate mailbox. When Mort found the shoddy file, he hastily scribbled a note to the chairman who had tendered the offending dossier—a note to the effect that it was apparent that this chairman did not have his office functioning at the level he would wish since “some junior clerk must have sent me this mess before you had a chance to consider it.” Subsequent submissions, from all departments, were carefully prepared!

THE MOVE TO BERKELEY

In the late 1970s, Mort decided to leave Delaware. This decision was not based on any professional dissatisfaction with the University of Delaware. He simply wanted to live in an urban setting. While several distinguished universities tried to recruit him, he chose the University of California at Berkeley, joining the faculty in 1981. The diversity and academic excellence that characterizes Berkeley, together with the cultural opulence and natural beauty of the Bay Area, proved to be the determining factors.

Upon arriving at Berkeley, Mort established a polymers and composites research program in conjunction with the Lawrence Berkeley National Laboratory. This is now a vibrant program with a principal focus on anisotropic polymers and polymer-surface interactions that has many principal investigators working on diverse problems ranging from field-theoretic descriptions of the statistical physics of polymers to issues pertinent to large-scale processing. Mort runs the program like a benevolent dictator.

The emphasis of Mort's research at Berkeley has shifted toward more experimental work. In the 1980s, there were two parallel efforts in his group:

large-scale computations of viscoelastic fluid flows and complementary experimental work. The computational work was done largely in collaboration with Roland Keunings (now Professor at The Catholic University of Louvain). Many interesting things emerged from the Denn laboratory in these years, but perhaps the most comprehensive and exciting studies concerned the flow of fiber suspensions^[13] and viscoelastic jet breakup.^[14] Theoretical and computational work on the rheology of fiber suspensions involved a synergistic collaboration with David Boger in Melbourne, whose group did the complementary experiments. Computational and analytical work done in Mort's group, combined with pre-existing experiments, solved many aspects of the viscoelastic jet-breakup problem.

Mort developed a very strong interest in the rheology and fluid mechanics of liquid crystalline polymers, a subject that is still a central focus of study in his laboratory. He made the decision in the late 1980s to abandon, for the moment, computational and theoretical work in this area and to focus exclusively on experimental work, because he strongly believed that there were many issues in this field that were not understood even phenomenologically. As such, he decided that complex algorithm development was not fruitful until some of the relevant questions were understood at the simplest physical and phenomenological level. Mort also decided that such an understanding could only be obtained via well-designed experiments. Over the past few years, Mort's lab and those of others have produced experimental data that (in Mort's view) have begun to provide the phenomenological understanding of liquid crystalline polymer rheology that he believed was missing five years ago.

The study of extrusion instabilities has been a major focus of Mort's research for years.^[15] During the past decade he has emphasized the role of the material of construction of the extrusion die on melt flow, particularly phenomena associated with failure of the no-slip boundary condition. Mort's innovative work in this area has combined adhesion theory, rheology, and surface spectroscopies ranging from XPS to ATR/FTIR in an effort to understand how surface chemistry and physics affect flow. He has had the satisfaction in recent years of seeing enough activity generated by his contributions (e.g., a paper on adhesion and slip in polymer melts,^[16] that he views as his most significant work of the decade) that his own papers have become secondary sources.

In his early years at the University of Delaware, Mort worked with a small number of students and sometimes with

single investigators in various parts of the world; there were few collaborations involving joint supervision of students. The greater emphasis on state-of-the-art experiments, and perhaps the character of the Berkeley campus, have led to much more collaborative work in recent years. He collaborates extensively with Jeff Reimer in using NMR spectroscopy to probe polymer structure. He has also collaborated with Clay Radke, Alex Bell, David Soane, Miquel Salmeron, and Susan Muller.

***In his early years. . . ,
Mort worked with a
small number of students
and sometimes with
single investigators in
various parts of the
world; there were few
collaborations involving
joint supervision of
students. The greater
emphasis on state-of-the-
art experiments, and
perhaps the character of
the Berkeley campus,
have led to much more
collaborative work in
recent years.***

TEACHING AND PROFESSIONAL ACTIVITIES

The Berkeley years have also seen Mort giving much of his effort and time to professional service and mentoring junior faculty in the department. In the late 1980s and early 90s, the Berkeley department had an eclectic group of young faculty (mostly assistant professors) doing exciting research as well as conceiving and teaching new courses. They were also a feisty bunch and respectfully challenged some of the existing ways of doing things. Mort, at least fifteen years senior to the oldest member of this group of renegades, was the leader of the pack. He took time out to mentor many of these young faculty, even if their research areas were quite different from his own. It is perhaps fair to

say that the success this group of now not-so-young faculty has realized can be partly attributed to the supportive and intellectually dynamic environment created by Mort and a few other senior faculty at Berkeley. Today, Mort continues to play a supportive role to the next generation of untenured faculty at Berkeley.

Over the years, Mort has served the chemical engineering profession in a variety of ways. For six years (1985-91) he was the sole editor of the *AICHE Journal*, and he worked hard to streamline the journal's operation. It is fair to say that when he handed the baton to Matt Tirrell, the *Journal* had regained its stature as one of the flagship journals of our profession.

Mort has served on innumerable review panels, editorial boards, and national committees of the AIChE, National Research Council, and other organizations. He is not just a warm body when it comes to these activities. He spends time to consider the various issues, he does his homework, and he contributes actively to the task at hand. His thoughts on the evolution of the profession of chemical engineering^[17] reveal that he worries about deep issues pertaining to the future of our profession. His article, "The Identity of Our Profession," may be controversial, but no one would deny that it is thoughtful.

Mort served as department chairman at Berkeley for three years (1991-94). He is very interested in curriculum development and modification and continues to serve as the conscience of the department in this regard. After stepping down from the chairmanship, we all expected Mort to take a breather and concentrate purely on teaching and research; however, this plan seems to have gone awry, as he has now taken over as editor of the *Journal of Rheology*.

Mort's former students and postdocs are profitably employed in industry, academia, and national laboratories. Perhaps a sign of the fact that he is "maturing" is the many former students and postdocs who are now in academia. These include Benny Freeman (NC State), Alejandro Rey (McGill), Jim Ultman (Penn State), Rakesh Jain (Harvard), Roland Keunings (C.U. Louvain, Belgium), Davide Hill (Notre Dame), Wen-Ching Yu (former dean of engineering at Tunghai University, Republic of China), Bob Fisher (UConn), Doug Kalika (Kentucky), Glenn Lipscomb (Toledo), Doug Bousfield (Maine), Rakesh Jain (Harvard), and S.J. Lee (Seoul National University, Korea).

Mort's remarkable achievements as a teacher, a researcher, and a responsible member of the profession have been recognized through a multitude of awards and honors, including a Guggenheim Fellowship, the Professional Progress and William H. Walker awards of the AIChE, the Bingham medal of the Society of Rheology, a Fullbright Lecture, and the Chemical Engineering Lectureship Award of the American Society for Engineering Education. In 1986 Mort was elected to the National Academy of Engineering.

Mort has a policy of introducing his seminars with a brief exposition of how his work complements that of his colleagues and how it was intended to contribute to wider departmental goals of teaching and research. This act of unselfish and unusual devotion to his colleagues is not one that he discusses, but it has been brought to our attention by faculty from other institutions who have heard his presentations. This devotion—to his profession, to his students, to his department—is a thread running through all his activities.

Mort continues to serve the profession and the chemical engineering department at Berkeley by his exemplary standards in research and teaching, by generously giving of his time to mentor young faculty, and by looking after the *Journal of Rheology*. Mort is happily married to Vivienne Roumani-Denn, head of the Berkeley Earth Sciences and Map Library. Mort and Vivienne enjoy living in the Bay

area and often welcome young faculty and their families to their home for a pleasant evening and panoramic bay views. They have six children between them: Matthew (practicing law in Wilmington), Susannah (works for the District Court in San Francisco), Rebekah (writes for Gannett papers in Westchester County, NY), Aryeh (a financial analyst for Smith-Barney in New York), Dania (a student at UCLA), and Natan (a student at Berkeley High School). The chemical engineering faculty at Berkeley are glad that Mort's thoughtful voice will be around in the coming years to help face and overcome the challenges that await us.



Mort and Vivienne at home, 1995.

ACKNOWLEDGMENTS

We thank colleagues at Berkeley and Delaware for sharing some of their recollections and thoughts regarding Morton M. Denn.

REFERENCES

1. Ultman, J.S., and M. M. Denn, *Trans. Soc. Rheol.*, **14**, 307 (1970)
2. Joseph, D.D., M. Renardy, and J.C. Saut, *Arch. Rat. Mech. Anal.*, **87**, 213 (1985)
3. Denn, M.M., and G. Marrucci, *AIChE J.*, **17**, 101 (1971)
4. Metzner, A.B., and G. Astarita, *AIChE J.*, **13**, 316 (1967)
5. For example, see Roisman, J.J., and M.M. Denn, *AIChE J.*, **15**, 454 (1969); Sun, Z.S., and M.M. Denn, *AIChE J.*, **18**, 1010 (1972)
6. Larson, R.G., E.S.G. Shaqfeh, and S.J. Muller, *J. Fluid Mech.*, **218**, 573 (1990)
7. Denn, M.M., C.J.S. Petrie, and P. Avenas, *AIChE J.*, **21**, 791 (1975)
8. Denn, M.M., "Fiber Spinning," in *Computational Analysis of Polymer Processing*, J.R.A. Pearson, S. Richardson, eds., Elsevier Applied Science Publications, 179 (1983)
9. Devereux, B.M., and M.M. Denn, *Ind. Eng. Chem. Res.*, **33**, 2384 (1994)
10. Denn, M.M., and T.W.F. Russell, *Introduction to Chemical Engineering Analysis*, Wiley (1972)
11. Denn, M.M., *Process Fluid Mechanics*, Prentice-Hall (1980)
12. Denn, M.M., and T.W.F. Russell, *Chem. Eng. Ed.*, **7**, 117 (1973)
13. Lipscomb, G.G., D.U. Hur, D.V. Boger, and M.M. Denn, *J. Non-Newtonian Fluid Mech.*, **26**, 297 (1988)
14. Bousfield, D.W., R. Keunings, G. Marrucci, M.M. Denn, *J. Non-Newtonian Fluid Mech.*, **21**, 79 (1986)
15. For example, see Denn, M.M., *Ann. Rev. in Fluid Mech.*, **22**, 13 (1990); Denn, M.M., ASEE Chemical Engineering Division Award Lecture, *Chem. Eng. Ed.*, **28**, 162 (1994)
16. Hill, D.A., T. Hasegawa, and M.M. Denn, *J. Rheology*, **34**, 891 (1990)
17. Denn, M.M., in C.W. Colton, Ed., *Perspective in Chemical Engineering (Advances in Chemical Engineering, 16)*, Academic Press, 565 (1991) p

THE MASS TRANSFER BOUNDARY LAYER WITH FINITE TRANSFER RATE

MORTON M. DENN

University of California • Berkeley CA 94720-1462

Mass transfer with finite rates is usually passed over with only a brief mention in undergraduate transport courses because of the complexity of the coupled problem in mass and momentum transport. Solutions to classical problems are available; Bird, Stewart, and Lightfoot (BSL),^[1] for example, present an elegant similarity solution for simultaneous heat, mass, and momentum transfer in a laminar boundary layer. The similarity solution is of necessity numerical in the final stages, and the form is sufficiently complex in structure that it is difficult to obtain insight to the underlying physical process in a straightforward manner.

I have found that it is much more effective to introduce students, undergraduate and postgraduate alike, to the concept of finite transfer rates through the von Karman-Polhausen (vK-P) approximation. Undergraduates have often seen the method previously in their study of fluid mechanics (e.g., Denn^[2]). With graduate students I precede this material with a scaling analysis to obtain the basic structure of the relation between the Sherwood, Schmidt, and Reynolds numbers (Denn^[3]). Standard texts often use the vK-P method for mass transfer boundary layers, but they fail to take advantage of one of its most significant pedagogical features: the finite-rate problem is no more complex than the uncoupled one. While there is no question but that the exact solution, as

given in BSL, is to be preferred for accuracy, the important structural features of the coupled solution are more clearly revealed through the simple analytical expression afforded by the vK-P approach.

The solution given here is not completely new; the problem was considered within a broader class, for example, by Spalding.^[4,5] The analogous transpiration cooling problem in heat transfer was analyzed in part by Yuan and Ness.^[6] I believe it is useful, however, to present the specific case of finite mass transfer in laminar flow over a flat plate in a form that is easily accessible to students, who would find the original literature on vK-P solutions as difficult as the exact solutions. In that regard, this paper might be thought of as a lesson plan and a possible supplement to a course text.

PROBLEM FORMULATION

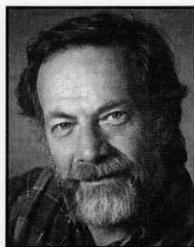
Consider flow of an incompressible Newtonian fluid with constant physical properties over a flat plate at zero angle of incidence. The flow direction is x and the transverse direction y . The surface contains a soluble species A, while the fluid phase is an ideal mixture of A and B. It is implicit in the standard problem formulation (cf BSL, p. 608 ff) that the molecular weights of A and B are equal ($M_A = M_B$). The overall continuity, momentum, and species continuity equations are, respectively,

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \quad (1)$$

$$v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} = \nu \frac{\partial^2 v_x}{\partial y^2} \quad (2)$$

$$v_x \frac{\partial x_A}{\partial x} + v_y \frac{\partial x_A}{\partial y} = D_{AB} \frac{\partial^2 x_A}{\partial y^2} \quad (3)$$

where



Morton M. Denn is Professor of Chemical Engineering at the University of California, Berkeley, and Head of Materials Chemistry and Program Leader for Polymers in the Materials Sciences Division of the Lawrence Berkeley National Laboratory. He received a BSE from Princeton University in 1961 and a PhD from the University of Minnesota in 1964, followed by a postdoctoral year at the University of Delaware. A profile of Professor Denn can be found elsewhere in this issue.

I believe it is useful . . . to present the specific case of finite mass transfer in laminar flow over a flat plate in a form that is easily accessible to students, who would find the original literature on vK-P solutions as difficult as the exact solutions. In that regard, this paper might be thought of as a lesson plan and a possible supplement to a course text.

v_x, v_y = x- and y-components of velocity, respectively
 x_A = mole fraction of A
 ν, D_{AB} = kinematic viscosity and binary diffusivity, respectively

Boundary conditions are

$$y=0: v_x=0, x_A=x_{A0}, N_B=0 \quad (4a,b,c)$$

$$x \leq 0 \text{ and } y \rightarrow \infty: v_x=v_\infty, x_A=x_{A\infty} \quad (4d,e)$$

where

$v_\infty, x_{A\infty}$ = "free-stream" values of velocity and mole fraction, respectively ($x_{A\infty}$ will often be zero)

x_{A0} = equilibrium or saturation level of A in the fluid phase at the surface $y=0$

N_B = molar flux of B

It is also useful to record the molar flux of the transferring species A at $y=0$ as

$$N_{A0} = \frac{\rho v_{y0}}{M_A} = - \frac{c D_{AB}}{1-x_{A0}} \frac{\partial x_A}{\partial y} \Big|_{y=0} \quad (5)$$

where v_{y0} is the transverse velocity at $y=0$ and c is the total molar concentration. Because $M_A = M_B$, $\rho = M_A c$. Equation (5) establishes the coupling between the mass and momentum equations.

It is convenient to use the dimensionless variables

$$u = \frac{v_x}{v_\infty}, \quad v = \frac{v_y}{v_\infty}, \quad w = \frac{x_{A0} - x_A}{x_{A0} - x_{A\infty}} \quad (6a, b, c)$$

Note that u and w range from zero to unity, but this is not true of v , so these are not appropriate variables for a scaling analysis (cf Denn^[3]). The dimensionless form of Eq. (5) is

$$v_0 = \frac{D_{AB}}{v_\infty} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \frac{\partial w}{\partial y} \Big|_{y=0} \quad (7)$$

Equations (1) through (4) then become

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (8)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \left(\frac{\nu}{v_\infty} \right) \frac{\partial^2 u}{\partial y^2} \quad (9)$$

$$u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} = \left(\frac{\nu}{v_\infty Sc} \right) \frac{\partial^2 w}{\partial y^2} \quad (10)$$

$$y=0 : u=w=0 \quad (11a, b)$$

$$x \leq 0 \text{ and } y \rightarrow \infty : u=w=1 \quad (11c, d)$$

where $Sc = \nu/D_{AB}$ is the Schmidt number. When $Sc = 1$,
 Spring 1996

Eqs. (9) and (10) for u and w are identical with identical boundary conditions for any v , so it follows immediately that $u = w$ and the dimensionless velocity and concentration profiles are the same.

vK-P FORMULATION

The vK-P approach converts the differential equations to an integral form. Firstly, the continuity equation is integrated to obtain

$$v_y = v_0 - \int_0^y \frac{\partial u}{\partial x} dy \quad (12)$$

Equations (9) and (10) are then integrated from $y=0$ to $y=\infty$; with some manipulation and the use of Eqs. (8) and (12), we obtain the starting point:

$$v_0 + \int_0^\infty \frac{\partial}{\partial x} [u(u-1)] dy = - \frac{\nu}{v_\infty} \frac{\partial u}{\partial y} \Big|_{y=0} \quad (13)$$

$$v_0 + \int_0^\infty \frac{\partial}{\partial x} [u(w-1)] dy = - \frac{\nu}{v_\infty Sc} \frac{\partial w}{\partial y} \Big|_{y=0} \quad (14)$$

We have assumed continuity of $\partial u/\partial y$ and $\partial w/\partial y$ throughout $0 \leq y < \infty$. This is a subtlety that should be addressed in the classroom because it can become a problem for some students subsequently.

The vK-P approximation is based on two fundamental hypotheses. Firstly, one assumes the asymptotic approach to free-stream conditions can be replaced by well-defined boundary layers $\delta(x)$ and $\delta_c(x)$ for velocity and concentration, respectively. For $y \leq \delta(x)$ [δ_c] the velocity (concentration) varies continuously from the surface condition to the value at $y=\infty$; for greater values of y the velocity (concentration) is constant. Secondly, one assumes that u and w are unique functions of $y/\delta(x)$ and $y/\delta_c(x)$ respectively; this is a similarity assumption that is in fact rigorous for the problem at hand, but generally not for other problems in which the vK-P approach is employed. Students usually need some discussion of the physical meanings of both these (independent) assumptions. We therefore write u and w as the functions

$$u = \phi[y/\delta(x)], \quad y \leq \delta; \quad u = 1, \quad y > \delta \quad (15a)$$

$$w = \psi[y/\delta_c(x)], \quad y \leq \delta_c; \quad w = 1, \quad y > \delta_c \quad (15b)$$

The functions ϕ and ψ must be continuously differentiable and satisfy boundary conditions

$$\phi(0) = \psi(0) = 0, \quad \phi(1) = \psi(1) = 1 \quad (16)$$

They are otherwise arbitrary. Equations (13) and (14) then become

$$\frac{v}{v_\infty Sc} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \frac{1}{\delta_c} \psi'(0) + \int_0^{\delta} \frac{\partial}{\partial x} \left\{ \phi \left(\frac{y}{\delta} \right) \left[\phi \left(\frac{y}{\delta} \right) - 1 \right] \right\} dy = -\frac{v}{v_\infty} \frac{1}{\delta} \phi'(0) \quad (17)$$

$$\frac{v}{v_\infty Sc} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \frac{1}{\delta_c} \psi'(0) + \int_0^{\delta_c} \frac{\partial}{\partial x} \left\{ \phi \left(\frac{y}{\delta} \right) \left[\psi \left(\frac{y}{\delta_c} \right) - 1 \right] \right\} dy = -\frac{v}{v_\infty Sc} \frac{1}{\delta_c} \psi'(0) \quad (18)$$

The upper limits of the integrals are δ and δ_c , respectively, because the integrands are identically zero beyond these points. It is important to remember that the argument of ϕ is $y/\delta(x)$ in both equations, whereas that of ψ is $y/\delta_c(x)$.

There is a very convenient variable change here, which is not necessary but simplifies the manipulations greatly. Students often have a problem with the details of the calculus. Define $\xi = y/\delta(x)$ in Eq. (17) and $\xi = y/\delta_c(x)$ in Eq. (18). The range of both integrals is then from $\xi = 0$ to $\xi = 1$; terms and operations involving only x are independent of ξ and can be taken outside the definite integrals. We thus obtain

$$\frac{v}{v_\infty Sc} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \frac{1}{\delta_c} \psi'(0) + \frac{d\delta}{dx} \left\{ \int_0^1 \phi(\xi) [\phi(\xi) - 1] d\xi \right\} = -\frac{v}{v_\infty} \frac{1}{\delta} \phi'(0) \quad (19)$$

$$\frac{v}{v_\infty Sc} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \frac{1}{\delta_c} \psi'(0) + \frac{d\delta_c}{dx} \left\{ \int_0^1 \phi \left(\xi \frac{\delta_c}{\delta} \right) [\phi(\xi) - 1] d\xi \right\} = -\frac{v}{v_\infty Sc} \frac{1}{\delta_c} \psi'(0) \quad (20)$$

Now define $\Delta = \delta_c/\delta$, where we assume Δ is a constant. This assumption requires a consistency check later. With a bit of rearrangement, Eqs. (19) and (20) then become

$$\frac{1}{2} \frac{d\delta^2}{dx} \left\{ \int_0^1 \phi(\xi) [\phi(\xi) - 1] d\xi \right\} = -\frac{v}{v_\infty} \left[\phi'(0) + \frac{1}{\Delta Sc} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \psi'(0) \right] \quad (21)$$

$$\frac{1}{2} \frac{d\delta_c^2}{dx} \left\{ \int_0^1 \phi(\Delta\xi) [\psi(\xi) - 1] d\xi \right\} = -\frac{v}{v_\infty Sc} \left[1 + \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \psi'(0) \right] \quad (22)$$

The right-hand sides and the coefficients in braces on the left are all constants in these equations for specified ϕ and ψ , so the square-root dependence of the boundary layer development is established. For $(x_{A0} - x_{A\infty})/(1 - x_{A\infty}) \ll 1$ the problems uncouple, in that Eq. (21) involves only fluid-mechanical variables. We can write the solution to the coupled problem as

$$\delta^2 = \frac{-\frac{2v}{v_\infty} \left(\phi'(0) + \frac{1}{\Delta Sc} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \psi'(0) \right) x}{\int_0^1 \phi(\xi) [\phi(\xi) - 1] d\xi} \quad (23)$$

$$\delta_c^2 = \frac{-\frac{2v}{v_\infty Sc} \left[1 + \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \psi'(0) \right] x}{\int_0^1 \phi(\Delta\xi) [\psi(\xi) - 1] d\xi} \quad (24)$$

The equation for Δ is obtained by setting $\Delta^2 = \delta^2/\delta_c^2$; this ratio is clearly independent of x , establishing that Δ is indeed a constant.

CLOSED-FORM SOLUTION

The functions ϕ and ψ are typically taken to be polynomials, usually cubics. The structure of the solution is best revealed by taking $\phi(\xi) = \psi(\xi) = \xi$, since in that case Δ simply factors out of the integral involving $\phi(\Delta\xi)$. There is a problem at $\xi = 1$, where the derivatives are not continuous, which will be a concern to some students, but it is a technical detail; the function can be taken as linear arbitrarily close to $\xi = 1$ and then rounded suitably to provide continuity of the derivative without changing the integrals in Eqs. (13) and (14) by more than an infinitesimal amount. With

$$\phi = \psi = \xi, \quad \phi' = \psi' = 1, \quad \text{and} \quad \int_0^1 \xi(\xi - 1) d\xi = -\frac{1}{6}$$

we have

$$\delta^2 = \frac{12v}{v_\infty} \left[1 + \frac{1}{\Delta Sc} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \right] x \quad (25)$$

$$\delta_c^2 = \frac{12\nu}{v_\infty \Delta Sc} \left[1 + \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \right] x \quad (26)$$

and

$$\Delta^3 Sc + \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \Delta^2 = 1 + \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \quad (27)$$

To first order in $(x_{A0} - x_{A\infty})/(1 - x_{A0})$ the solution to Eq. (27) is

$$\Delta \sim Sc^{-\frac{1}{3}} \left[1 + \frac{1}{3} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \left(1 - Sc^{-\frac{2}{3}} \right) \right] \quad (28)$$

Defining $Re_x = xv_\infty/\nu$ we obtain, to the same order in $(x_{A0} - x_{A\infty})/(1 - x_{A0})$,

$$\frac{\delta}{x} = 3.46 Re_x^{-\frac{1}{2}} \left[1 + \frac{1}{2} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) Sc^{-\frac{2}{3}} \right] \quad (29)$$

$$\frac{\delta_c}{x} = 3.46 Re_x^{-\frac{1}{2}} Sc^{-\frac{1}{3}} \left[1 + \frac{1}{6} \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \left(2 + Sc^{-\frac{2}{3}} \right) \right] \quad (30)$$

MASS-TRANSFER COEFFICIENT

There are a number of ways in which the mass-transfer coefficient can be defined. In my opinion the transport coefficients need to be viewed as quantities defined by experiment; for mass transfer the interfacial flux N_{A0} and driving force $x_{A0} - x_{A\infty}$ are the quantities that can be measured in principle, so the proper operational definition for the mass transfer coefficient k_x is

$$k_x \equiv \frac{N_{A0}}{c(x_{A0} - x_{A\infty})} \quad (31a)$$

BSL choose to define the transport coefficient relative to the molar average velocity, so their definition would be

$$k_x^* = \frac{N_{A0}(1 - x_{A0})}{c(x_{A0} - x_{A\infty})} \quad (31b)$$

Failure to distinguish between these definitions can cause a great deal of confusion. (There is a dimensionality difference between both these definitions and those used by BSL; k , as defined here, has dimensions of velocity.) The Sherwood number, $Sh_x = xk_x/D_{AB}$, then follows from Eqs. (7) and (30) to first order as

$$Sh_x = 0.289 Re_x^{\frac{1}{2}} Sc^{\frac{1}{3}} \left[1 - \frac{1}{6} \left(2 + Sc^{-\frac{2}{3}} \right) \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \right] \quad (32)$$

(The coefficient for the exact solution is 0.332. The form

$Re^{1/2}Sc^{1/3}$ follows directly from scaling arguments; cf Denn.^[3]) The correction relative to the low-flux limit is therefore

$$\frac{Sh_x}{Sh_{0x}} = \frac{1}{1 - x_{A0}} \left[1 - \frac{1}{6} \left(2 + Sc^{-\frac{2}{3}} \right) \left(\frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \right) \right] \quad (33)$$

There are two contributions to the correction term. The term in brackets, which reflects the contribution of the driving force, is less than unity; this term corresponds to the effect of thickening the boundary layer with a constant driving force, hence reducing the gradient for diffusion. The denominator term $1 - x_{A0}$ reflects the convective contribution to the total flux. The net effect of the two terms is to increase the Sherwood number relative to the zero-flux limit. (This is most easily seen by setting $x_{A\infty} = 0$, $x_{A0} \ll 1$, in

which case $\frac{Sh_x}{Sh_{0x}} \sim 1 + \left(\frac{2}{3} - \frac{1}{6} Sc^{-\frac{2}{3}} \right) x_{A0} > 1$.) A Sherwood

number based on k_x^* would decrease, however, since the thickened boundary layer decreases the diffusive flux.

CONCLUDING REMARKS

I have found this example to be effective in introducing students to the concept of corrections for finite mass-transfer rates because it uses a methodology with which they are (or should be) familiar and leads to a reasonably accurate result in closed form. I like to emphasize the limitations inherent in the usual assumption of no surface flux and the breakdown of transport analogies at high rates of mass transfer. The boundary layer, approached in the manner outlined here, is an excellent vehicle for doing so, and at no "cost" since the same methodology is likely to be used for the solution of the uncoupled problem in order to establish the $Sc^{1/3}$ dependence in the Sherwood number relation.

ACKNOWLEDGMENT

Warren Stewart called my attention to the papers by Spalding and Yuan.

REFERENCES

1. Bird, R.B., W.E. Stewart, and E.N. Lightfoot, *Transport Phenomena*, Wiley, New York, NY (1960)
2. Denn, M.M., *Process Fluid Mechanics*, Prentice Hall, Englewood Cliffs, NJ (1980)
3. Denn, M.M., *Process Modeling*, Wiley, New York, NY (1986)
4. Spalding, D.B., "Mass Transfer in Laminar Flow," *Proc. Roy. Soc. (London)*, **A221**, 78 (1954)
5. Spalding, D.B., "Mass Transfer from a Laminar Stream to a Flat Plate," *Proc. Roy. Soc. (London)*, **A221**, 100 (1954)
6. Yuan, S.W., and N. Ness, "Heat Transfer in a Laminar Compressible Boundary Layer on a Porous Flat Plate with Variable Fluid Injection," Tech Memorandum P1B-15, Project Squid, Polytechnic Institute of Brooklyn, Sept. 1, 1950 □

A LABORATORY EXPERIMENT THAT ENHANCES ENVIRONMENTAL AWARENESS

KEN K. ROBINSON, JOSHUA S. DRANOFF
Northwestern University • Evanston IL 60208-3120

The goals of the senior-year chemical engineering laboratory course at Northwestern University are to nurture critical thinking skills so that students can analyze open-ended problems, to develop and improve the student's technical communication skills, and to provide experience with typical equipment and instrumentation. We try to accomplish these goals in one academic quarter by requiring student teams of 3-4 students each to run five different experiments (from a current total of eight, listed in Table 1), to prepare a detailed written technical report for each experiment, and to present an oral report as the final exam. Furthermore, we attempt to stimulate their thinking skills by purposely giving students very brief instructions for most of the more standard experiments so they cannot simply "follow the cookbook" in running the experiment.

A laboratory course essentially similar to ours, frequently designated as a "Unit Operations Laboratory," has been a core course in chemical engineering curricula for many years. Thirty years ago, most chemical engineering instructional laboratory equipment was large and multi-storied, while to-

Ken Robinson has been a Lecturer at Northwestern University since 1993, with primary responsibility for the undergraduate chemical engineering laboratory. He received his BS and MS from the University of Michigan and his DSc from Washington University. He has worked in industry for both Amoco (1973-1992) and Monsanto (1965-1973).



Joshua Dranoff is Professor of Chemical Engineering at Northwestern University, where he has been on the faculty since 1958. He received his BE degree from Yale University and his PhD from Princeton University. His research interests are in chemical reaction engineering and chromatographic separations.

© Copyright ChE Division of ASEE 1996

We continually try to keep the experiments relevant by phasing out older ones and introducing newer ones that expose students to problems of the day. . . . Environmental awareness is an important theme and provides the motivation for the experiment discussed in this article.

day the scale is usually smaller and more compact due to safety and space considerations. The unit operations laboratory has normally been the first opportunity for students, particularly those not in a cooperative education program, to observe and operate larger-scale equipment and to begin to appreciate some of the more realistic situations they might face in industry. Some of the concepts we hope they learn in the course are an appreciation of the difference between steady-state and transient operation and how long it can take to reach steady state in particular equipment, knowing when a computerized data acquisition system is giving realistic and reliable numbers, and how to use and draw reasonable conclusions from data that are limited and far from perfect.

In this connection, Dahlstrom, in a recent article on the history of chemical engineering education,^[1] described the important role played by Olaf Hougen through his practical approach to education. Hougen's Principles^[2,3] have particular relevance to the way we prepare chemical engineering students for industrial careers with such laboratory courses. Although Hougen listed twelve principles, the three most applicable to this course are

- If you can't find relevant problems to give the student, then you shouldn't be teaching the material to the students.
- Well-founded and well-tested empiricisms are to be preferred over theories that have only a limited range of applicability.
- It is vital for engineers to know how to solve problems with limited or incomplete data.

We continually try to keep the experiments relevant by phasing out older ones and introducing newer ones that

expose students to problems of the day. For example, computerized data acquisition is standard in most petroleum refineries and chemical plants, so we have incorporated personal computers with data acquisition hardware/software for all of the more sophisticated experiments. Environmental awareness is another important theme and provides the motivation for the experiment discussed in this article.

FLUID-BED INCINERATION

We have developed a new fluid-bed incineration experiment for the chemical engineering laboratory that we believe gives students useful exposure to solid and liquid waste treatment. A recent article by J. Mullen^[4] described the use of fluid-bed incinerators for the destruction of hazardous wastes. Such an incinerator basically consists of a shallow fluid bed in which air, fuel, and combustible waste are fed into the bottom where combustion of fuel and waste takes place in the fluid bed medium, typically sand. The suspended solids/gas mixture has a vigorous boiling action and high heat transfer, which results in rapid and thorough mixing of the air, fuel, waste combustibles, and fluid-bed media. Some of the advantages of the fluidized bed combustor compared to other types of incinerator include efficient combustion, easy control, the ability to handle variable feeds, and much lower emissions of NO_x and metals; the fluid bed typically operates at temperatures between 1400-1650°F. Combustibles are exposed to full combustion temperature for 5-8 seconds or more.

We decided to build a bench-scale fluid-bed incinerator for incorporation into our laboratory course. The basis for the design was provided by Ecova Inc., a subsidiary of Amoco Oil located in Denver, Colorado. They had developed a bench-scale unit for establishing design parameters on a commercial facility in Kimball, Nebraska, rated at an annual capacity of 45,000 tons of hazardous waste. This commercial unit was started up in the spring of 1994 but has since been shut down due to unfavorable economics and potential liability from its operation.

The laboratory unit was constructed in the Northwestern University shop over a three-month period. The entire unit, complete with instrumentation, was built for slightly less than \$10,000.

Spring 1996

(An additional \$5,000 would be required for analytical equipment, specifically a dual-column gas chromatograph and electronic integrator.) The unit is simple to run and seems to fit well into the framework of the chemical engineering laboratory.

Experimental Unit Design • The main elements of the experiment unit are the fluid-bed combustor, the feed systems for air, methane fuel, and waste material, and the analytical equipment. The feed gas monitoring and mixing chamber and the combustion unit are located in a fume hood.

The fluid-bed incinerator is a vertically-mounted 3-inch stainless tube, which is 24 inches long. It is enclosed with two semi-cylindrical electric heaters (3.5-inch ID), with a total heating capacity of 3.4 kilowatts, and 2 inches of insulation. Bed temperature is controlled with a solid-state Omega temperature controller that cycles current through a 220-volt relay and into the electrical heating jacket around the incinerator. The chamber is surmounted by a particle disengaging zone in which the diameter increases to 8 inches.

As shown in Figure 1, there are four ports along the combustor where temperature and pressure drop can be measured. Type K (chromel-alumel) thermocouples have been inserted into the ports, and a pressure tap, connected with a Swagelok® tee, is at the same location. Pressure drops are

measured using three Omega Engineering differential pressure (DP) cells with a full range of 20 inches water. The unit as described has a high height-to-diameter ratio that leads to bed slugging and a small freeboard height. For improvements in the design, we would suggest that the diameter be somewhat enlarged (by about 4 inches) and the freeboard increased to prevent fluidizing media from being blown out of the bed.

A side injection port is provided near the base of the incinerator to introduce wastes such as newsprint, plastic, rubber, and liquid hydrocarbons. It consists of a horizontal stainless-steel pipe with two 1/2-inch ball valves, one to seal the injection chamber from the hot fluid bed and the other to allow access to the injection chamber for loading with solid wastes. A piston is mounted on the end of a 1/4-inch tube

TABLE 1
Northwestern Laboratory Experiments

- ▶ Pressure drop in fixed and fluidized beds
- ▶ Heat transfer in double-pipe and shell-and-tube exchangers
- ▶ Mass transfer in a wetted wall column
- ▶ Sucrose inversion in a plug-flow catalytic reactor
- ▶ Propanol dehydration in a differential catalytic reactor
- ▶ Fractional distillation of methanol-water in a multi-tray glass column
- ▶ Mixing and residence time distribution for a tank-in-series system
- ▶ Unsteady-state heat conduction in solids

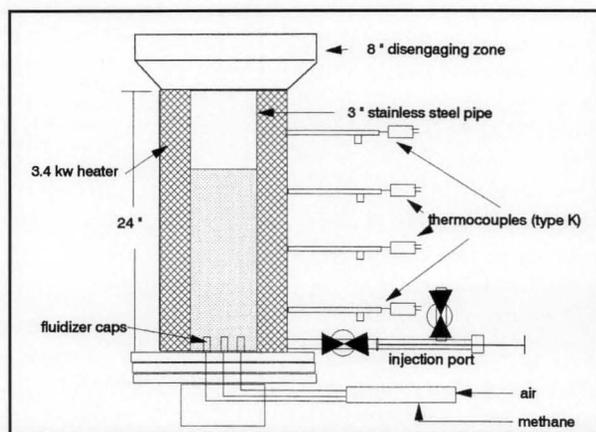


Figure 1. Fluid bed incinerator

that slides through an end cap. For solid-waste injection, the piston is advanced forward through the body of the ball valve and stops with the piston flush with the inside wall of the combustion chamber. If liquid wastes are to be pumped into the incinerator, the piston is left advanced and a small syringe pump feeds liquid into a tee located at the handle end and through the center of the tube.

The bed is filled with Mulcoa 47-20X-50S, an aluminosilicate medium (25x35 mesh) that can withstand higher temperatures than regular silica sand, but sea or river sand can also be used if desired since many commercial incinerators use it.

Air and methane from cylinders are metered through rotameters, premixed in-line in a mixing chamber, and then fed cold into the bottom of the fluid-bed unit through four jets consisting of sintered porous fluidizer caps. The caps are arranged with three in an equilateral triangle pattern and the fourth in the center. Excess air is used to fluidize the bed and lower the combustion temperature. Additional air purges are located on either side of the side injection port to clear the region of fluid bed media when a waste injection is being performed. A layout for the gas distributor is given in Figure 2.

Flue gas from the unit is analyzed with a dual column gas chromatograph equipped with two different columns and thermal conductivity detectors. One column contains molecular sieve 5A and measures oxygen, nitrogen, methane, and carbon monoxide, while the other contains Porapak[®]Q and primarily determines the amount of carbon dioxide and water in the flue gas. A Teflon gas bag is used to collect an average sample of the flue gas and is similar to the bag sample concept used for testing automobile emissions. Typical chromatograms for these two columns are shown in Figure 3. (The most important flue gas components for this experiment are carbon monoxide and carbon dioxide.)

OPERATING PROCEDURES

Start-up of Unit:

- Air flow is initiated at a moderate rate, somewhat less than the fluidization velocity.
- The temperature controller is then turned on and set to 800°F. In about thirty minutes that temperature is reached, and the temperature set point is increased to 1300°F, which is slightly higher than the auto ignition temperature of methane (1200°F).
- Once the temperature reaches 1300°F, the air flow is increased to start fluidization of the bed and methane is slowly introduced into the mixing chamber outside the bed. Ignition of the methane starts immediately. For the 3-inch diameter bed, we use 1 SCFM of air and 0.07 SCFM of methane (air/fuel ratio of about 16).

A small mirror is positioned above the top of the unit so that the bed can be observed during operation. "Light-off" of the incinerator is usually accompanied by a soft pop, after

which the bed begins to glow red. The set point to the temperature controller can now be shut down since methane combustion will sustain the temperature in the bed with no external heating. The adiabatic flame temperature of methane with a stoichiometric amount of air (9/1 air-to-fuel ratio) is 3500°F, so it is important to feed the fluidization air in excess or the incinerator will get too hot and severely damage the steel combustion chamber as well as fuse the bed medium into large aggregates. We suggest that a temperature controller with a high-limit switch be used to shut off fuel gas flow with a normally closed solenoid valve.

Once the bed has reached steady-state operation, wastes may be injected by means of the injection port at the bottom of the fluid bed. As noted earlier, the injection port has two stainless-steel ball valves (1/2-inch). The valves are mounted so that one serves as a vertical loading port, while the other is used to keep fluid bed media out of the injection chamber.

- To load the port with waste, the vertically mounted ball valve is opened and about 10 ml of waste material is dropped in.
- The valve is then closed and an air purge is started on both sides of the horizontal ball valve to keep the valve free of granular solids.
- The horizontal ball valve is then opened and a push rod is manually advanced toward the bed to pass through the ball valve and inject the solid waste into the fluid bed.

Injection of solid wastes is clearly an *unsteady-state* process; consequently, the observations made with solid wastes

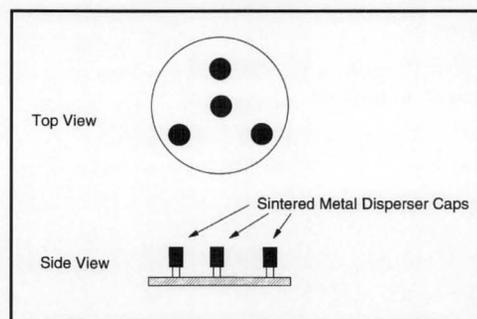


Figure 2. Gas distributor layout.

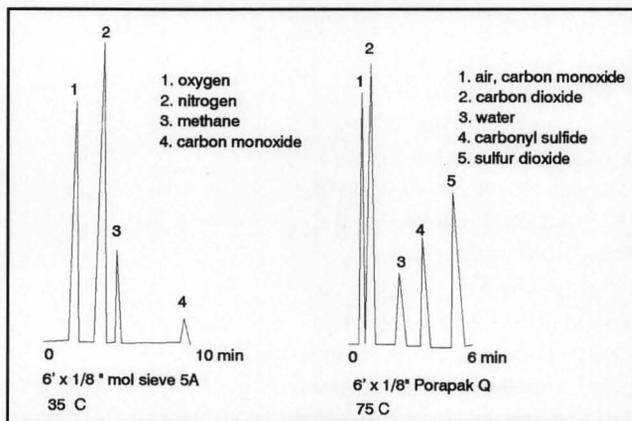


Figure 3. Gas chromatograph analysis of flue gas.

will be mostly qualitative. But steady-state conditions can be achieved with liquid wastes. The push rod consists of a hollow tube connected to a disc with a small hole drilled in it; this can be used with liquid wastes that are pumped continuously into the incinerator. It should be noted that the combustion reactions of the fuel as well as the waste materials produce large heat releases; dealing with these is considerably more stimulating and challenging for the student than the more typical use of air and water as process media in the laboratory setting.

THEORY AND DATA ANALYSIS

This experiment provides opportunities for application of several different types of theory and data analysis.

Minimum Fluidization Velocity and Pressure Drop • The student needs to estimate the minimum fluidization velocity before starting operation of the incinerator. We find that you cannot exceed this value too much or granular material is entrained and blown out of the bed. Once the fluidization air rate is established, this controls how much methane fuel can be added for heating the unit.

Combustion and Adiabatic Flame Temperature

$$U_{mf} = \frac{d_p^2(\rho_s - \rho_g)g}{1650\mu} \quad \text{Re}_p \leq 20$$

$$U_{mf}^2 = \frac{d_p(\rho_s - \rho_g)g}{24.5\rho_g} \quad \text{Re}_p \geq 1000 \quad (1)$$

where U_{mf} = minimum fluidization velocity
 d_p = particle diameter
 ρ_g = gas density
 ρ_s = particle density
 μ = fluid viscosity
 g = gravitational constant
 Re_p = particle Reynolds number, $(\rho_g U_{mf} d_p) / \mu$

Stoichiometry • We typically use methane as the fuel gas, but propane will also function well. But the heating value of propane is significantly higher than methane, so this must be taken into consideration.



Adiabatic Temperature Rise • The target temperature for the unit is 1400-1800°F, so the student must calculate the adiabatic temperature rise for some typical fuel gas feed rates. The approximate equation for temperature rise with an energy balance yielding the more exact expression is

$$\Delta T = \frac{-\Delta H_r}{C_p} \quad (2)$$

where ΔT = temperature rise
 ΔH_r = heat of reaction
 C_p = specific heat of feed stream

GENERAL PROCEDURE FOR TESTING AND ANALYSIS

The fluid-bed incinerator experiment is reasonably challenging for even the best students. Consequently, we recommend that it be placed midway or later in the laboratory course so that the students will be more experienced with operating procedures and not require such close supervision. We usually schedule the laboratory experiments so that the students have operated the fixed/fluid bed experiment first and have some appreciation of what fluidization is by observing it in a clear tube with small glass packing. They are then better prepared to run the fluid-bed incinerator unit and to address the aspects of fluidization, combustion, and incineration of industrial wastes.

The experiment is performed over two laboratory periods of eight hours each. During the first period, the students start up the unit, measure temperature and pressure drop across the bed and analyze the flue gas by filling the Teflon bags, and then inject samples into both columns of the gas chromatograph with a gas syringe. During the second period, wastes are fed into the fluid bed through the injection port. Small pieces of polystyrene, plastic eating utensils, and rubber stopper are first dropped into the top of the bed to observe incomplete combustion at short residence times (typically yielding black particulates or soot). Then the same materials are injected into the bottom port of the fluid bed incinerator for essentially complete combustion under conditions of longer residence time and better heat transfer. Also, a bag sample of the exhaust is taken while the waste injection is performed to compare to the operation with no waste incineration. The following questions are proposed for the students to think about and answer in their reports:

- Does an energy balance on the unit predict an outlet temperature close to what was observed?
- How do the measured pressure drops and temperature distribution relate to theory?
- Does the minimum fluidization velocity calculation agree with what you actually observed?
- Discuss the flue gas composition and the distribution of carbon monoxide/carbon dioxide.
- Do you think significant nitrogen oxides (NOx) formed in the fluid bed incinerator?
- What about dioxin formation? Besides hydrogen and carbon, what is the key element needed to make dioxin in the flue gas and what temperatures favor its formation?

CONCLUSIONS

The new fluid-bed incinerator experiment has lived up to our expectations and has given a new spark to the array of teaching experiments used for the unit operations laboratory. It seems to satisfy a number of the criteria in Hougen's Principles. More specifically, it is a relevant industrial prob-

Continued on page 160.

DESIGN COMPETITION FOR SECOND-YEAR STUDENTS*

A Retrospective

W. A. DAVIES

University of Sydney • Sydney, New South Wales, Australia 2006

After spending their high-school years solving theoretical problems for which there are always some sort of defined “right answers,” students tend to arrive at the university with the belief that there is a right answer to *everything*. In the practical world, however, there is an inestimable number of ways of going wrong while the number of ways of going right are preciously few. This is one reason why our department includes formal practical training throughout all stages of the curriculum. A less formal exercise, but also serving the same purpose, is our annual “Second-Year Design Competition.”

The Competition provides students with a genuine challenge in process engineering, allowing them to show off their ingenuity in the face of a strict set of constraints. It also offers an entertaining spectacle for the onlookers, good cash prizes for the winners, public humiliation for failure, and triumph for the victors. It has become a keenly anticipated highlight of the academic year.

In this paper we will look at some of the more successful Competitions from the past dozen years, the organization needed to mount them, and how they have benefitted both the department and the faculty of engineering as a whole.

Organization • Normally, the class of about eighty students is asked to form into groups of two students each. Solo entries are permitted, but the complexity of demonstrating



Wayne Davies took his degrees in the same department where he now combines the roles of part-time honorary lecturer and full-time operator of a consulting business. He has interests in biologicals, minerals, and petroleum, and has experience in everything from antibodies to zinc and from LPG to LPS. He would like to hear from any readers who intend to mount a design competition. He can be reached by e-mail at “davies@chem.eng.usyd.edu.au” or by regular mail.

[The Competition] offers an entertaining spectacle for the onlookers, good cash prizes for the winners, public humiliation for failure, and triumph for the victors. It has become a keenly anticipated highlight of the academic year.

the design usually requires two people. About a month before the Competition date and just before a mid-semester break, each student is given a handout describing the Competition rules and constraints. They then have a break of one or two weeks in which to design their entry. In most cases there is some equipment used to test the entries and the essential features of this are put on display in a special cabinet in public view. This cabinet also contains Competition memorabilia such as photographs of the past events and actual parts of winning entries from previous years.

Prizes and Sponsorship • We make a point of inviting an industrial sponsor to the Competition. The sponsors, whose products are in some way relevant to the Challenge, donate prize money in return for a novel form of lunchtime entertainment and the opportunity to put their company name in front of potential clients. Sponsors have always been eager to attend and to make some observations of their own at prize-giving time.

Designing the Competitions • “Using familiar materials for unsuitable purposes in an impossible time frame in front of a noisy crowd” is the basis of the design Competitions. Many entries have been taken from the domestic environment and given a twist such as the “Egg Separator,” the “Cut-the-Soap,” and “Transporting the Beer” Competitions. Conventional process engineering has inspired three tasks in the form of water pumping, pneumatic conveying, and heat exchanger design. Risk engineering gave us the “Bursting Disk” and “Extinguish the Flame.” Nearly any familiar con-

* Published in an earlier form in “Chemical Engineering in Australia,” September 1995

cept can be made into a competition topic by imparting an awkward constraint. We never seem to be short of ideas.

We choose second-year students deliberately. These students are still at the beginning of the course and have not yet studied subjects such as unit operations, thermodynamics, and control. Lacking the formal benefit of these skills, second-year students offer refreshing novelty because they are still essentially free from the constraints of conventional wisdom and are not so sophisticated in outlook that their designs are conservative and predictable. This increases the likelihood of the unexpected.

Judging • To be successful in all respects, as a spectacle and as an assessable effort, the Competition must have a definite criterion for winning or losing, and for best visual impact, this criterion should be immediately obvious to the spectators. Devices or processes that fail or succeed spectacularly are best. Criteria which involve lengthy calculations of some performance index are less so. For this reason, we have endeavored to move away from measuring an optimum such as "performance per unit weight of entry," preferring a design to simply work well despite, or because of, its size.

Prizes • The winning team, the runner-up, and the most deserving team receive prizes made up from the entry fee, which is usually \$5 per team, plus \$300 to \$400 donated by the sponsor. The winners also receive certificates that document their accomplishment in suitable style. Students tend to value these certificates as much as the cash.

Academic Assessment • A potential 5% bonus marks in Chemical Engineering II are offered for participating in the Competition. Students do not have to participate, but we find that offering such a bonus gives them the necessary incentive, which they may not have otherwise. As a result, the majority of the class participates.

MOST MEMORABLE COMPETITIONS

The Explosion Vent Bursting Disk (1992)

The task was to design a vessel and equip it with a bursting disk such that it would vent safely, an explosion occurring inside the vessel. The conditions were:

The vessel would receive by injection through a port, a precise amount of liquid fuel (e.g., 2 ml of acetone). The explosion would then be vented safely by blowing off the

integral bursting disk. The loudest report as measured by a pair of sound pressure meters would win.

To reduce risk to the participants, all operations were handled by a departmental technician suitably equipped with full-face mask and gloves. To guard against the vessel already containing fuel (which might augment the sound level achieved), the technician also fired the spark before fuel was introduced into the vessel. A premature explosion would disqualify the entry. To guard the spectators, a circular plexiglass panel open at the top was placed around the entry.

In their design, the students had to consider several things: a means of vaporizing the fuel so as to achieve a good fuel/air mixture; the volume of the vessel required to achieve a good fuel/air ratio; the area of the bursting disk; and its firmness of attachment to the vessel.

The winning entry was a 4-liter paint can containing a handful of rocks that had been previously warmed in an oven (see Figure 1). Foam insulation around the can helped keep the rocks warm until the time of the test. The lid of the can acted as the bursting disk. When tested, this entry gave a maximum sound pressure of over 100 dB at 3 meters, with the lid being blown vertically to a height of about 5 m.

An entry that did not win, however, was more spectacular. It consisted of a paint-solvent can of about 4 liters and not much else. The bursting disk was the cap of the can, which was comparatively small at about 40-mm diameter. When tested, the entry gave out a tremendous bang and simply disappeared. At this point the spectators looked left and right for the missing can, then realizing that there was only one direction it could possibly have gone, they simultaneously looked up to see the can still heading upwards and getting smaller all the while. The can naturally fell to earth again, heading for a space that spectators hurriedly cleared. The base of the can was found on the test table. As a result, the entry was disqualified because the bursting disk failed to vent the explosion safely. The judges suspected that the can had been filled with oxygen.

The Egg Separator (1988)

A quieter competition required students to design a device that would automatically separate the white from the yolk of an egg. A whole unbroken egg would be inserted into the device, and all operations after that would occur automatically, with the result that the white and the yolk would be

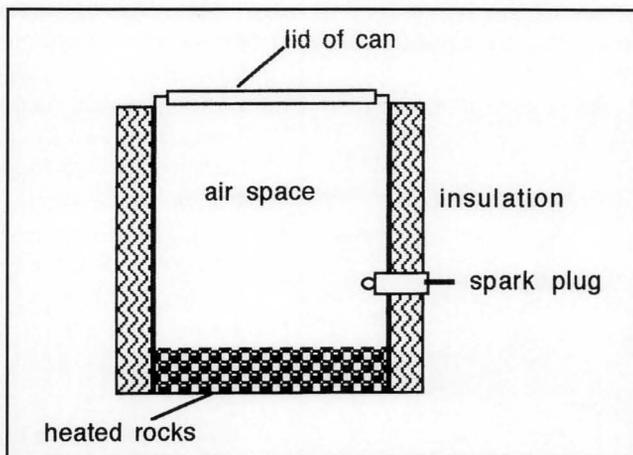


Figure 1. Schematic diagram of the winning entry in the Bursting Disk Competition of 1992.

delivered into two waiting receptacles, *e.g.*, two petri dishes. The students had to design a device that would break the egg and allow its contents to flow and to separate as they did so. Understanding and exploiting the properties of unusual fluids was the major challenge of this exercise.

Several entries failed because their operation required manual intervention, most often to break the egg. Some failed because the egg would not flow across the separating device, or if it did, the yolk broke.

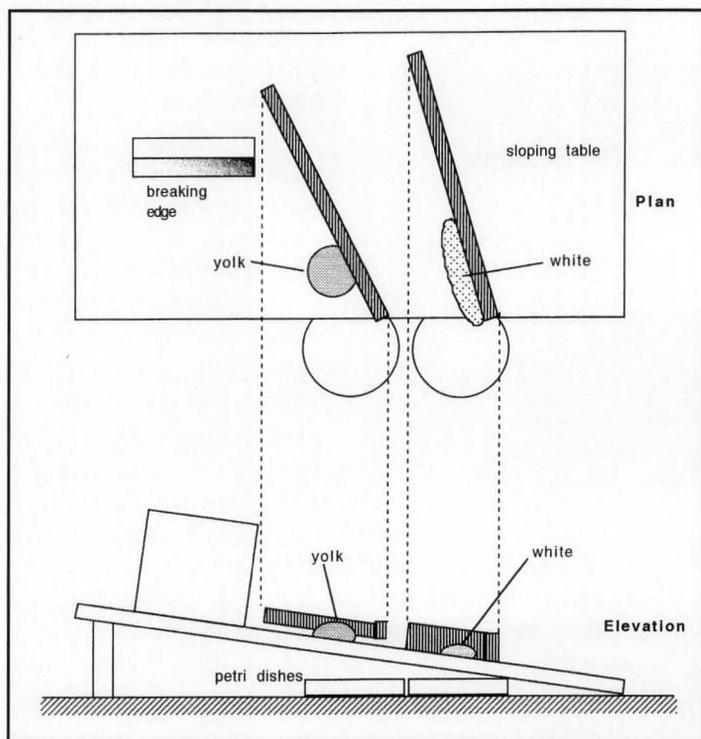


Figure 2. Schematic diagram of the winning entry in the Separate the Egg Competition of 1988.

There was a clear winner, however, who surpassed all expectations. It satisfied the design conditions in every detail and exploited the properties of the materials beautifully. In this design (see Figure 2), the egg was dropped via a chute onto a metal breaking edge pointing upward. Contact broke the egg, which then flowed down the sides of the edge onto a sloping table. Two barriers were positioned on the sloping table such that the flow of yolk and egg would continue by gravity. The first barrier was an underflowing weir that held back the yolk while the white flowed underneath, while the second barrier captured the white. Both barriers allowed the yolk and white to continue their flow to the edge of the sloping table where they were collected into separate petri dishes. When tested in front of an enthusiastic audience, the final plop of the yolk into its dish was greeted with thunderous applause.

The Bead Elevator (1991)

Planning, timing, and teamwork were especially required in this competition. The aim was to design a mechanical means of con-

veying foam beads from a ground-level feed bin to a receiver bin located on a platform 2 m above the ground. The fastest time to convey more than 95% of the beads, or failing this, the greatest quantity of beads moved in a 30-second period would be the winner. Students would need to understand the nature of pneumatic transport as well as to optimize the efficiency and operation of their design.

Many designs based on vacuum cleaners appeared on the day of competition, but none was as well calculated to succeed as the eventual winner. In most entries, an operator applied suction to the receiver bin via a hose inserted into a removable lid. Another hose was let down to the feed bin where the other operators could manipulate it. Ideally, the resultant air movement was supposed to suck up the beads and deposit them into the receiver bin. Several problems emerged with these designs, however. Frequently the hoses, being fairly narrow, clogged up with beads. In some cases the vacuum applied to the receiver bin was too great and



Figure 3. "They should have won!" Students face defeat graciously in the Bead Transport Competition (1991).

collapsed it by sucking it in. Hoses would fall out of their intended mountings, or the weight of the hose would pull the receiver bin over and spill the beads. Some entrants found that the beads did not remain in the receiver bin but continued on into the vacuum cleaner. This did no good for the flow of air, especially if the cleaner's dust bag had been removed. The most valiant attempt that did not work was



Figure 4. Encouragement Prize winners of the Extinguish the Gas Flame Competition (1994) brave the heat with the elegant nozzle-extension-on-a-pole.



Figure 5. Winners of the same competition show their style with baby stroller and gas bottle. The flame was put out in under five seconds.

based on an industrial blower. In it, the feed bin was pressurized and a large-bore hose conveyed beads to the receiver. Unfortunately, the pressure applied was too great for the flimsy plastic bin and its lid blew off in a white blizzard (see Figure 3). The entrants, who showed great courage in the face of defeat, received the Encouragement Award.

The winners had a different approach altogether. Their design was based on a rotary-motor mower in which a light-weight fan was substituted for the normal blade. A cardboard ducting system was attached beneath the mower so that the beads could be neatly sucked up. The outlet of the mower (where the grass is normally ejected into the catcher) was fitted with a duct that led to a lid fitted over the receiver bin (which was firmly held down by an operator). This lid was fitted with a gauze mesh to allow air out of the bin while retaining beads within. After starting the mower, the whole operation was over in eighteen seconds, and the recovery of beads was nearly perfect. This winning entry demonstrated the advantage of establishing clear design parameters and good teamwork, as well as thorough planning and testing.

A joke entry came in the form of a firework that was placed in the feed bin. The resulting explosion blew beads out of the bin and in a total duration of twelve seconds, half a handful was transported to the receiver bin. This entry did not come in last.

Extinguish the Gas Flame (1994)

This was possibly the most entertaining spectacle of all. The aim was to extinguish a luminous flame of LPG emerging from a 25-mm nozzle at full cylinder pressure. This competition was advertised as providing "a serious flame" later estimated at about 40 kwatts of heat. Competitors were allowed within a minimum radius of 3.5 m of the flame and were given thirty seconds. The fastest time to extinguish the flame would be the winner.

Many entrants tried to smother the flame with a variety of devices held by poles over the nozzle. Many devices caught fire, and others did not succeed when the flame found a way around them and ignited elsewhere. Some attempted to pour water down the nozzle, but the gas pressure simply blew it back out. An ingenious entry (winner of the Encouragement Award) used a piece of pipe that fitted neatly over the nozzle and extended it some 400 mm (see Figure 4). Manipulating this pipe attached to the end of a pole, the entrants placed it over the nozzle, causing the flame to jump to the end of the extension. The entrants then quickly jerked the extension upward

and off the nozzle, lifting the flame away from the gas source. The flame went out accompanied by loud acclamation from the audience. Unfortunately, the unwieldy apparatus was difficult to manipulate at the distance involved and the entrants took too much time.

The winning team carried out their task with inouciant ease. Their entry consisted of a bottle of carbon dioxide gas resting in a baby stroller that could be pushed by a long pole (see Figure 5). One member opened the valve, allowing the gas to flow, while the other poled the stroller out to the flame. In less than five seconds the flame was out. Although the crowd was greatly impressed, there was some resentment from the other contestants since the competition conditions stipulated that no commercial fire extinguishers were to be used. Indeed, this entry used a commercial principle, but it was not itself a commercial extinguisher—so it won.

Antigravity Water Transfer (1995)

The Competition for 1995 was based on moving water from one vessel to another using a pump. Normally, this is a routine task, but there was a catch. Entrants could not put any external power to the pump, so all of the energy for pumping the water had to be derived from the head of water itself. Water was supplied in an 800-liter tank, filled to the brim about 1.6 m above ground level. A receiver was arranged so that its entry point was at the same height as the water in the tank. Obviously, siphons would not work.

Many entrants designed variations of the hydraulic ram. This well-established invention inspired by the phenomenon of “water hammer”^[1] converts the momentum of a falling water column into pressure energy when the flow is suddenly stopped by a valve. The increase in pressure then elevates a fraction of the water to a higher level. Because the hydraulic ram is readily found in textbooks, the organizers expected most entries would be based on this principle, and, in fact, the winner was. One of the delights of the Competition, however, is being amazed by the unexpected and, as hoped for, several entries exploited entirely different principles.

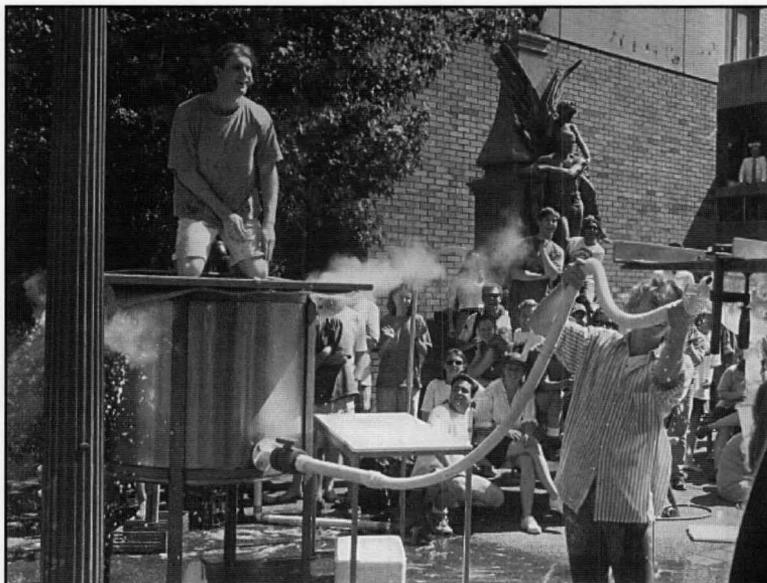
One entry (which won second place) caused falling water to pressurize the air in a vessel of about 20-liter capacity situated at ground level. This increased air pressure was transmitted via a tube to a second vessel at a higher level that had been previously filled with water from the tank. The air pressure then pushed water out of the second vessel into the receiver. Other less successful but amusing en-

tries included a flimsy cardboard-and-rubber-band turbine that turned half a dozen times, got waterlogged, and stopped, meanwhile giving the operators a bath (see Figure 6), a great slow-working piston pump, reminiscent of a Boulton and Watt steam engine, which did not even fill up in the thirty seconds, and an unofficial entry by graduate students that used solid carbon dioxide pellets and a lid on the tank to pressurize the water, forcing it directly to the receiver (shown in Figure 7). Al-



Figure 6. Typical of the more whimsical entries in this cardboard and rubber-band turbine pump seen in the Water Transport Competition (1995). Despite the team's well-drilled display, no water entered the receiver.

Figure 7. Unofficial entries often appear with the intention of getting around the rules. In the same competition and amid clouds of CO₂ vapor, graduate students successfully put a lid on the tank and transport 8 liters of water in 30 seconds.



though the resultant flow was spectacular, using the heat energy of the water was a too-clever interpretation of the rules and it was disqualified.

The winning entry, based on the hydraulic ram principle, was a well-researched and well-designed device that transported 2.6 liters of water in thirty seconds. The winners had consulted an engineer (actually, one of the team's parents), and having gotten the general idea, made their entry from PVC pipe and fittings, a 2-liter plastic soft-drink bottle, a squash ball, a marble, and a piece of garden hose. Unlike many of the others, this team hardly got wet at all.

A COMPETITION FOR VISITORS

A related competition is held from time to time for visitors to the department on University Open Days. This competition requires a more spontaneous approach, and because there is no time for the contestants to design and prepare an entry, construction materials are provided and the assigned task is simple.

Our favorite example involves a hot-air balloon for which contestants must design and build a burner of greatest efficiency. This burner contains a small quantity (say, 25 ml) of fuel, such as ethanol. The burner is attached by metal wires to the inside of the hot-air balloon and the fuel is ignited. The longest duration aloft wins. The balloon, made from plastic foil, is only 2 m tall and slides up and down a taut wire inside an atrium within the building. Typical materials provided are aluminum foil, wire, cotton wool, scissors, pliers, etc. Obviously, the lighter the burner, the less is the effort required to lift it, but the more flimsy it is. The shape of the burner is important in determining the time aloft. An initial burst of heat is generally required, and heat should then taper off for maximum duration. Several minutes aloft is not uncommon.

Typically, the response to this competition overwhelms the organizers. On our first attempt, there was a line of contestants waiting for thirty or more minutes to have a go at it. In subsequent years we had four balloons going at once and still had no time to relax. Entries were widely variable and imaginative, but typically the simplest designs did best.

DISCUSSION

Students take the challenge seriously, using imagination and intuition together with some formal engineering to devise a wonderful range of exotic devices. The Competition not only broadens their scope but also gives them an excellent excuse to have some fun. It also performs a service in socializing students. For most, this is their first time in a public exhibition in front of their peers. Although there may be some degree of humiliation in defeat, this soon passes as the rewards, as ever, are in participating.

Other Competitions not described in this paper have been based on various examples of process unit operations. They

have included optimizing a distillation rig for producing drinking water (1987), operation of a precision soap-cutting device (1989), transporting beer using only the pressure in the can (1990), and optimizing a simple heat exchanger (1993).

Originally, most Competitions involved a means of transporting matter or energy by some method that could be optimized. More recently, two of the Competitions have been based on the area of risk in the process industries (*e.g.*, the Bursting Disk and Extinguish the LPG Flame). There is an obvious extra level of excitement in this type of competition and we will continue to include them, mindful always of the necessary safety precautions.

Despite the general levity of the occasion, there is usually some scholarly relevance. In the bursting disk competition of 1992, the solvent can that exploded and rocketed was noted to have relevance to a major industrial fire in which a solvent storage tank ruptured at its base, similarly exploding and rocketing.^[2] The 1994 Competition to extinguish the LPG flame had relevance to the oil fires in Kuwait after the Gulf War. Interestingly, the winning entry used a similar principle to extinguish the fire that was used by the team of experts on the real thing.

One lesson might be, "Do your research carefully, especially if deception is the aim." One of the entries in the soap-cutting Competition of 1989, a mysteriously modified cardboard box produced two perfect halves from a whole cake of soap in record time and looked like winning. But it was not to be. A spirited audience observed, and the judges confirmed, that the cake inserted into the device was pale pink while the two halves that emerged were white!

The Competition's real message is, I like to think, that Experience is the best teacher. Until they reach the university, nearly all of the students' academic experiences have been theoretical. The concept of actual catastrophe never seems to emerge. In the real world, however, catastrophe is always ready to exploit the unready. Perhaps most students do not realize the Competition's lessons at the time, but some will in the future—we hope, to their benefit.

ACKNOWLEDGMENTS

I would like to especially thank the workshop and technical staff of the department who have given many hours of their time to build equipment, supervise the Competition, and enforce safety requirements on the day. In addition, learned colleagues Dr. T.A.G. Langrish, Prof. D. Reible, and Dr. B. Walsh, acting as masters of ceremonies, have given invaluable support. The Competition flourished under the championing of Prof. R.G.H. Prince.

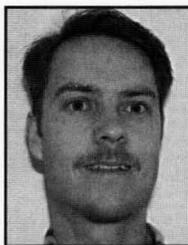
REFERENCES

1. Smith, B.E., "Building a Model Hydraulic Ram," *Modeltec*, pg. 8, April (1995)
2. Thomas, F., "Coode Island: Vapour Recovery to Blame?" *The Chemical Engineer*, 506, pg. 17, October (1991) □

DEMONSTRATIONS TO COMPLEMENT A COURSE IN GENERAL ENGINEERING THERMODYNAMICS

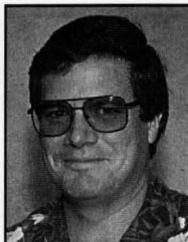
DOUGLAS J. DUDGEON,* J.W. ROGERS, JR.
University of Washington • Seattle WA 98195-1750

At the University of Washington, the College of Engineering offers a lower-division course in general engineering thermodynamics. The course is part of the core engineering curriculum that students are supposed to take prior to applying for admission to a department. As such, it serves many departments in the College, most of which provide instructors for the course. Chemical and mechanical engineering students take the course in their sophomore year to satisfy departmental admission requirements and to serve as a foundation for further study of advanced thermodynamics in their respective programs. Students from other departments take the course to satisfy specific graduation requirements or to fulfill their elective engineering science credits. These students often do not enroll in the course until late in their senior year; thus the sections usually contain a very broad cross-section of students in various stages



Doug Dudgeon received his BS in chemical engineering from the University of California, Berkeley (1987), and his PhD from the University of Washington (1995). At the UW he was twice awarded the McCarthy Prize for Excellence as a Teaching Assistant and was involved with the ECSEL project. His research interests include applications of non-Newtonian fluids and determination of these fluids' rheological properties.

J.W. (Bill) Rogers, Jr., is Professor of Chemical Engineering at the University of Washington. He received his BS in Chemistry (1975) and PhD in Physical Chemistry (1979) from the University of Texas. He spent eleven years at Sandia National Laboratories doing basic and applied research on energetic materials, thin film deposition and modification, and finally as Supervisor of the Ceramic Development Division, before joining the ChE Department at UW in 1991.



* Address: Kraft Foods Technology Center, 801 Waukegan Road, Glenview, Illinois 60025-4312

TABLE 1
Engineering Thermodynamics Schedule and Layout

Week	Topic	Demonstration
1	Basic concepts	Constant-volume thermometry
2	Properties of a pure substance	Critical state of carbon dioxide
3	1st law of thermodynamics (closed systems)	----
4	1st law of thermodynamics (open systems)	Hair dryer
5	2nd law of thermodynamics (closed and open systems)	Heat capacity ratio for air
6-7	Entropy, 2nd law efficiency	Efficiency of a compressor
8-9	Power and refrigeration cycles	Heat pump
10	Instructor's choice	---

of their undergraduate careers.

Engineering thermodynamics is a four-credit course that meets for three 50-minute lectures and one 110-minute quiz section per week. Prerequisites are two quarters of freshman chemistry (general), three quarters of freshman calculus with analytical geometry, and one quarter of freshman physics (mechanics) with a laboratory. The course content, outlined in Table 1, includes

- Concepts of units and dimensions, pressure, temperature, heat, and work
- Macroscopic properties of substances
- Principles of first-law analysis for closed systems
- Principles of energy analysis for open systems, including flow and shaft work
- Concepts of the second law of thermodynamics in its

... this class ideally should have a laboratory to accompany the lecture material. This would give students hands-on experience with the concepts presented in the lectures and would also expose them to engineering devices. Budget, space, and time considerations prohibit this, but we have found a reasonable substitute in a set of classroom demonstrations that can easily be integrated into the course sequence.

macroscopic form for open and closed systems and engineering devices

- *Power and refrigeration cycles*

The circumstances under which the course is offered make it pedagogically challenging. First, the various departments wish to emphasize topics that are relevant to their own program. For example, one department wants heavy emphasis on thermodynamic cycles, while another wishes to emphasize psychrometrics. As a result, it is difficult to obtain a consensus between the departments on course content, and it is difficult to coordinate among the various instructors to ensure a uniform coverage of the material. Coordination with local community colleges, which also offer the course and from which we receive transfer students, further complicates course administration. Second, there is a universal fear of the course material across the spectrum of students who take the course. Indeed, there are many new and unfamiliar concepts introduced in the course. Terms such as enthalpy and entropy may have been encountered before, but they are usually not well understood and it is difficult for the students to grasp such intangible concepts. This is compounded by the third problem, which is that few of the students have any mechanical skills and most have had very little laboratory experience. Because the material has a strong emphasis on engineering devices, many students find it difficult to comprehend how some of these devices function. Fourth, the course is very crowded and has little room for new material.

To improve comprehension, this class ideally should have a laboratory to accompany the lecture material. This would give students hands-on experience with the concepts presented in the lectures and would also expose them to engineering devices. Budget, space, and time considerations prohibit this, but we have found a reasonable substitute in a set of classroom demonstrations that can easily be integrated into the course sequence. We present below the set of demonstrations that were developed under the auspices

Spring 1996

of the National Science Foundation's "Engineering Coalition of Schools for Excellence in Education and Leadership" (ECSEL).

The set consists of demonstration hardware, notes for instructors, and student handouts where necessary. The demonstrations were developed with the concept that "seeing is believing" and that some familiarity with engineering devices will improve understanding and comprehension of the lecture material. Our criteria for developing the demonstrations were that they had to be inexpensive, easy to construct, portable, and completable in less than fifteen minutes of class time. In addition, each had to convey several key concepts from the lecture material. In the two years the demonstrations have been used, they have received excellent reviews from students and faculty alike.

► **Constant-Volume Thermometry** ◀

This classic apparatus may be used to demonstrate the absolute temperature scale and the ideal gas law. The constant-volume thermometer is based on Gay-Lussac's law (1802) that the temperature of a gas is proportional to its pressure at constant volume. Gay-Lussac's law is, of course, a special case of the ideal gas law. The goals of this demonstration are to illustrate Gay-Lussac's law and to estimate the value of the temperature at zero pressure, *i.e.*, the absolute zero of temperature.

The apparatus (see Figure 1) consists of a thin-tube water manometer, a stoppered 125-ml Erlenmeyer flask, a 1000-ml beaker, a digital thermometer, and a supporting stand. One end of the manometer is open to atmosphere and the other is connected to the flask through a short piece of Tygon® tube. For best results, it is important to use a thin-tube manometer (diameter less than 5 mm) and a short piece of tube to connect the manometer to the flask to minimize the volume of air that is not in the water bath. In addition to the apparatus, the instructor must supply approximately 2000 g of ice.

In order to establish the P-T proportionality, at least three data points are

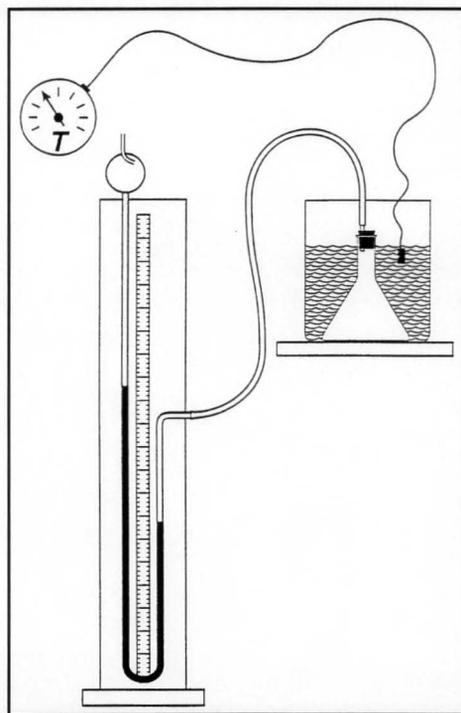


Figure 1. Schematic diagram of the constant-volume thermometer.

required, although it is easy enough to acquire more points. For the first point, the beaker is filled with room-temperature water and the flask is immersed in the beaker. After allowing the system to come to equilibrium, the pressure on the manometer and the temperature of the water bath are measured. For additional points, ice is added to cool the water to a lower temperature (it is usually necessary to pour off excess water). The final data point is obtained using a saturated ice/water solution (273 K, approximately 0°C). Of course, the system is not at constant temperature except at the end points of 273 K (0°C) and room temperature (approximately 295 K). But the change in temperature is sufficiently slow that its contribution to experimental error is negligible.

Gay-Lussac's law may be expressed as $T = a + bP$, where a and b are constants. Thus, a plot of the P-T data should give a linear result. Extrapolation to $P = 0$ gives a measure of absolute zero. With our system, using the procedure outlined above, consistently we have been able to come within 20 K of the true value, which is remarkable due to the simplicity of the apparatus and the large extrapolation involved. The demonstration also illustrates the use of a manometer to measure pressure and the concepts of differential, absolute, and gauge pressures.

► Critical State of Carbon Dioxide ◀

This demonstration allows a pure, two-phase mixture to be observed as it passes through the critical point. The apparatus was developed in 1959 by an undergraduate student at the University of Washington's Department of Mechanical Engineering;^[1] we merely added it to the current package of demonstrations. It consists of a sealed quartz tube containing a two-phase mixture of carbon dioxide (CO_2). The mixture is sealed into the tube at the critical molar volume ($0.0943 \text{ m}^3/\text{kmol}$), and when the contents are heated from room temperature (state 1) to a higher temperature (state 2), the mixture passes through the critical point (304.2 K, 7.39 MPa) as shown on the property diagram depicted in Figure 2. The meniscus is observed to pass into critical opalescence, then to disappear.

The tube is conveniently heated by placing it in a fixture that fits into the focal point of a surplus 35-mm film strip projector. Heat from the 150-W projection bulb raises the temperature of the mixture such that it reaches the critical state in about ten minutes. The optics of the projector are used to focus the meniscus onto a screen for viewing by the entire class. Similar designs have been reported recently in this journal.^[2] This demonstration illustrates the critical properties of a pure substance, the structure of property and phase diagrams, and the concept of quality for a two-phase mixture.

Because the sealed quartz tube contains a fluid at very

high pressure, this demonstration poses a significant explosion hazard, so appropriate safety procedures should be observed. As a minimum, the instructor should wear safety glasses, transport the tube in a shielded case, and quickly mount the tube into the projector (preferably before students are present). Once the tube is mounted, the geometry of the projector provides a blast shield against the effects of an accidental explosion. We suggest that before preparing a tube for this demonstration, interested readers should consult relevant literature^[2] and select a fluid with a lower critical pressure.

► First Law for an Open System ◀

This demonstration is the realization of a problem from the Çengel and Boles' textbook, *Thermodynamics: An Engineering Approach*, which is currently used for the course.^[3,4] The first law is used to determine the mass flow rate of air exiting a hair dryer. The apparatus consists of a hand-held hair dryer mounted on a stand and a Chromel-Alumel (type-K) thermocouple with an attached digital thermometer. The thermocouple tip should be located approximately 7-8 cm from the dryer exit and in the middle of the flow (radially). The tip should be no closer to the dryer exit since the temperature distribution of the air nearer the exit is not uniform and radiative heating of the thermocouple by the dryer's hot filament becomes a problem. The hair dryer is operated for two or three minutes to reach steady state, and the outlet (T_2) and inlet (T_1) temperatures are measured.

This is a simple application of the first law

$$\dot{Q} - \dot{W} = \dot{m}(\Delta h + \Delta ke + \Delta pe) \quad (1)$$

where

\dot{Q} , \dot{W} rate of heat transfer and work, respectively

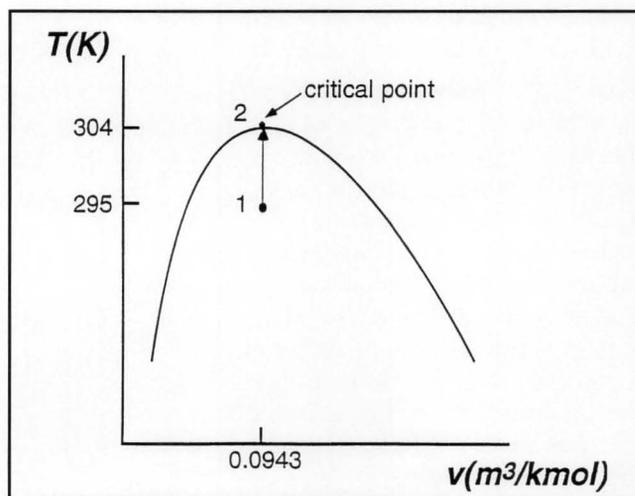


Figure 2. The T-v property diagram for CO_2 .

\dot{m} mass flow rate

$\Delta h, \Delta ke, \Delta pe$ change in specific enthalpy, kinetic energy, and potential energy, respectively

We make a number of assumptions for the analysis: negligible heat loss through the dryer's walls, negligible changes in kinetic and potential energy, steady state and uniform flow, that air is an ideal gas under these conditions, and that its heat capacity is constant over the measured temperature range. This gives

$$-\dot{W} = \dot{m}\Delta h = \dot{m}C_p(T_2 - T_1) \quad (2)$$

or, on rearranging,

$$\dot{m} = \frac{-\dot{W}}{C_p(T_2 - T_1)} \quad (3)$$

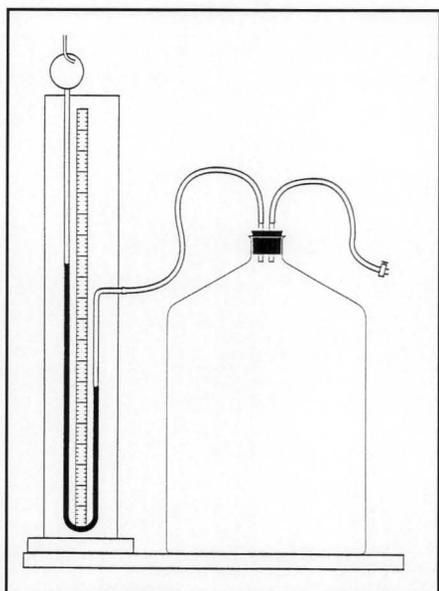


Figure 3. Apparatus for measuring the heat capacity ratio of air.

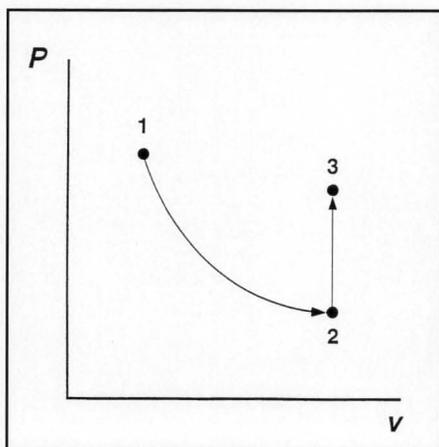


Figure 4. Pressure-volume diagram for the heat capacity ratio experiment.

where C_p is the heat capacity of air.

We further assume that negligible electric energy is consumed by the dryer's fan so the power delivered to the air is the electric power into the dryer, which was measured as 1176 W ($\pm 5\%$) out of class using a voltmeter and a clip-on ammeter. Typical temperatures measured are

$$T_1 = 22^\circ\text{C} (295\text{K}) \quad \text{and} \quad T_2 = 72^\circ\text{C} (345\text{K})$$

so that the mass flow rate works out to

$$\dot{m} \approx 0.023 \text{ kg/s}$$

This value is within 4% of the mass flow rate measured with a velometer. Because the cross-sectional area of the exit can be measured, the mass flow rate can easily be manipulated to give the average gas velocity and the volumetric flow rate to illustrate the relationship between these quantities, in addition to illustrating the first law. The principles and operation of a thermocouple are also shown, and if the thermocouple at the exit is moved radially, the assumption of uniform flow used in Eq. (1) can be relaxed and nonuniform flow can be demonstrated.

► Heat Capacity Ratio for Air ◀

This demonstration is a simplified version of an experiment given by Shoemaker, *et al.*^[5] The goal is to determine the heat capacity ratio

$$\gamma \equiv \frac{C_p}{C_v}$$

for air near standard temperature and pressure. The demonstration gives students experience with properties of an ideal gas, adiabatic processes, and the first law. It also illustrates how P-V-T data are used to measure other thermodynamic properties and how to measure differential pressure using a manometer.

The apparatus is illustrated in Figure 3 and consists of a stoppered, 19-liter (five-gallon) carboy and an open-tube, water-filled manometer. The carboy stopper is punctured by two pieces of glass tubing for connection to Tygon[®] tubing. One piece of tubing connects the carboy to the manometer, while the other is used to pressurize the carboy through a hose clamp. The water in the manometer is tinted with food coloring for better viewing.

The experiment involves a two-step process (see Figure 4):

Process 1-2: Expand the gas in the carboy adiabatically and reversibly from P_1 to P_2 .

Process 2-3: At constant volume, allow the gas to return to thermal equilibrium as its pressure changes to P_3 .

The system is initialized by opening the vent clamp, blowing into the carboy, and then closing the vent. An initial pressure of 16-18 inches H₂O (6.4 to 7.2 x 10⁻² Pa) is generally sufficient. The system is then allowed to reach thermal equilibrium (about fifteen minutes). This preparation may be done outside of the actual class time since it is not a part of the process outlined above.

For the demonstration, the initial pressure P_1 is read on the manometer. The carboy is momentarily unstoppered and then the stopper is replaced. This allows the gas in the carboy to expand as the pressure drops to atmospheric (P_2). Note that this expansion is approximately adiabatic and reversible.^[5] After 10 to 15 minutes, the system returns to thermal equilibrium once again and the final pressure P_3 is read on the manometer.

The analysis, which comes directly from Shoemaker, *et al.*,^[5] is lengthy but straightforward, and a handout is provided for the students. It will not be repeated here, but starting with the first law and the assumption of ideal gas behavior, the heat capacity ratio may be related to the measured pressures

$$\gamma = \frac{C_p}{C_v} = \frac{\ln P_1 - \ln P_2}{\ln P_1 - \ln P_3} \quad (4)$$

Although our apparatus is crude in comparison to that detailed by Shoemaker, consistently we are able to determine γ for air to within 5% of the reported value of 1.40.^[3]

► Efficiency of a Compressor ◀

The goal of this demonstration is to determine the second-law efficiency of a small compressor. Discussion may also center around the operation of a compressor (actually a pump, in our case), a Bourdon pressure gauge, and/or a gas flow meter.

The apparatus, shown schematically in Figure 5, consists of a 40-W reciprocating-piston pump that compresses air into a 3.5-liter tank. (The type of compressor is not important; any suitable compressor available from the university salvage pool will work.) The gas flow rate of the air exiting the tank is measured by a rotameter and controlled by a valve on the rotameter; this valve also controls the pressure in the tank. The tank pressure is measured with a Bourdon gauge, and a digital thermometer is used to measure the temperature both inside the tank and in the external environment.

In our apparatus, the pump generates pressures from 0 to 6 psig (101 to 142 kPa) and mass flow rates of air from 0 to 0.33 g/s, drawing approxi-

mately 40 W electrical power for any setting. The power consumption was measured (outside of class) to $\pm 5\%$ using a wattmeter. Operating at steady state, we observe no significant change in temperature between the inlet and the tank, indicating that this system is essentially isothermal.

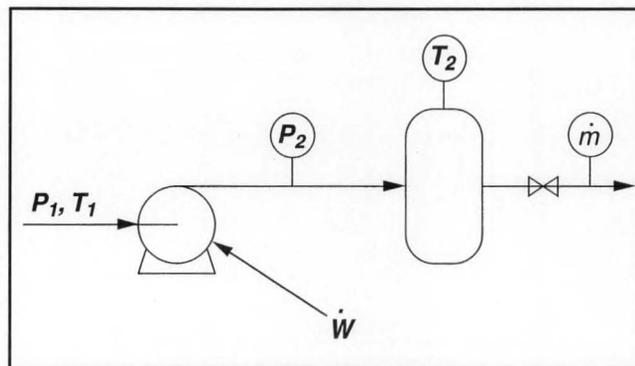


Figure 5. Schematic diagram of the apparatus for measuring the efficiency of a compressor (pump).

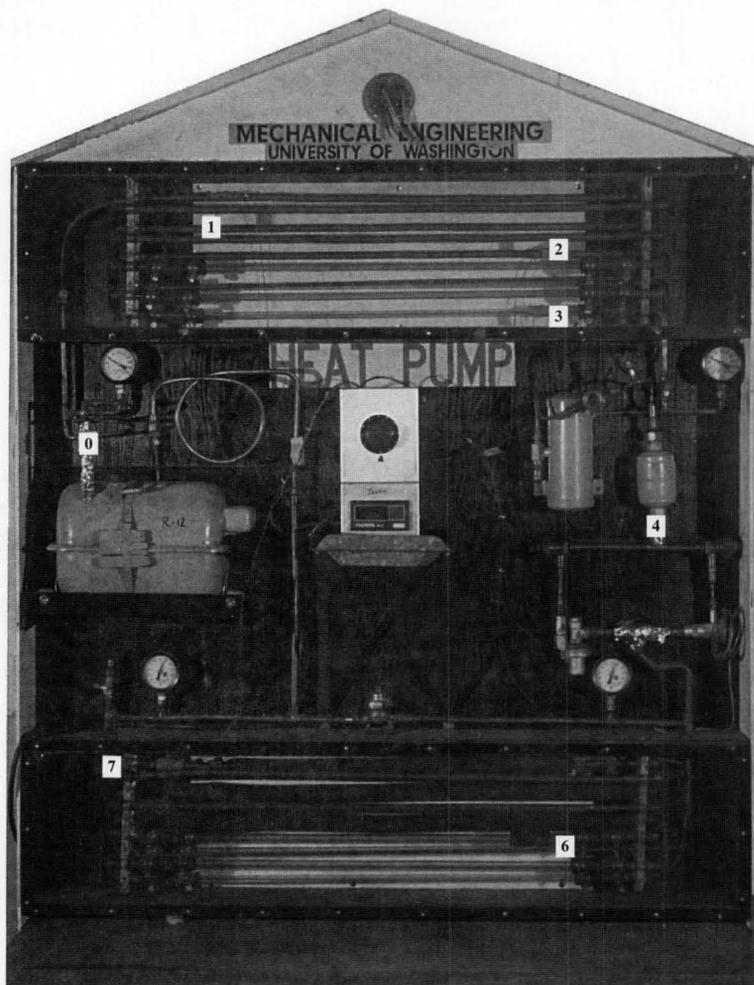


Figure 6. Photograph of the heat pump system showing (0) the compressor, (1,2,3) the condenser, (4) the dryer and expansion valve, and (6,7) the evaporator.

For purposes of analysis, the compressor comprises the thermodynamic system (control volume) and the working fluid is air. The second-law efficiency for a compressor is the ratio of the reversible work to the actual work

$$\eta_c = \frac{\dot{W}_{\text{rev}}}{\dot{W}} \quad (5)$$

The actual work, \dot{W} , we know to be -40 W. To obtain the reversible work, we start with the first law for a steady-flow system

$$\dot{Q} - \dot{W}_{\text{rev}} = \dot{m}(\Delta h + \Delta ke + \Delta pe) \quad (6)$$

and the second law for a reversible steady-flow system ($\dot{S}_{\text{gen}} = 0$)

$$\dot{m}\Delta s = \frac{\dot{Q}}{T_o} \quad (7)$$

These expressions are combined to eliminate \dot{Q} . Neglecting changes in kinetic and potential energy, we arrive at the following expression relating the reversible work to changes in enthalpy and entropy:

$$\dot{W}_{\text{rev}} = \dot{m}(T_o\Delta s - \Delta h) \quad (8)$$

If we assume an ideal gas, then the changes in enthalpy and entropy are easily calculated from the heat capacity of air and the measured temperature and pressure. Thus, the reversible work and the second-law efficiency of the compressor may be calculated. Typical values for our setup are $\dot{W}_{\text{rev}} \approx -6\text{W}$ giving $\eta_c \approx 0.15$. This is one of the few demonstrations that conveniently allows students to observe and quantify a change in entropy.

► Heat Pump ◀

Power and refrigeration cycles are an important topic of this course, and we have a working heat-pump cycle demonstration to illustrate the main principles of thermodynamic cycles. The heat pump was fabricated from a surplus refrigerator compressor, two cross-flow, air heat exchangers, and an expansion valve (see Figure 6). The heat-exchanger compartments of the condenser and evaporator are covered with Plexiglas® and several of the heat-exchanger tubes are constructed from glass to observe the changes in phase of the working fluid, refrigerant-12 (R-12) as it transits the cycle. Pressure gauges and thermocouples are included between processes in the cycle so that students can observe pressure drop and temperature changes associated with each process and compare it with property changes predicted from the property diagram of the refrigerant.

During operation, the evaporator operates at a pressure of 586 kPa (85 psia), the condenser pressure is 974 kPa (141 psia), and the temperature exiting the compressor is 357 K

(183°F). From these values and the R-12 property tables or diagrams, the students can calculate the coefficient of performance for the heat pump, the work supplied to the compressor assuming isentropic operation, the irreversibility associated with the expansion valve, etc. Discussion can also center around changes in expected performance if R-12 is replaced by the more environmentally friendly refrigerant-134a (R-134a), assuming the same amount of work is supplied to the compressor.

This demonstration does not fit in the same category as those discussed above; it is portable (but not small) and inexpensive, but relatively complicated to construct. It was constructed several years ago in the Department of Mechanical Engineering and was available for use in this class, so we have included it to round out the demonstration set.

EVALUATION

The demonstrations were designed to supplement each of the major sections of the course as shown in Table 1. The addition of the demonstration set to the lecture material was evaluated by two sections of students who took our offering of the course. The evaluation took the form of a set of questions prepared by the UW Office of Educational Assessment and the ECSEL assessment team. The students were asked to respond to four or five questions concerning the demonstrations and how helpful they had been in enhancing their understanding of the underlying thermodynamic concepts. On a scale of 0 to 5, the pooled average and standard deviation were 3.76 and 1.01, respectively, with 53 students responding. Verbal feedback from faculty who used the demonstrations has been uniformly positive.

ACKNOWLEDGMENTS

This work was conducted under the auspices of the National Science Foundation's ECSEL (Engineering Coalition of Schools for Excellence in Education and Leadership) Program, and the authors gratefully acknowledge their support. We also thank Professors Creighton Depew and Ashley Emery of the UW Department of Mechanical Engineering for development of the heat-pump system and the critical-point apparatus, respectively.

REFERENCES

1. Leichester, J.R., University of Washington (1959)
2. Marcotte, R.E., L.C. Zepeda, and D.L. Schruben, *Chem. Eng. Ed.*, **28**(1), 44 (1994)
3. Çengel, Y.A., and M.A. Boles, *Thermodynamics: An Engineering Approach*, McGraw-Hill Publishing Co., New York, NY (1994)
4. Shakerin, S., *Am. Soc. of Mech. Eng.*, **20**, 63 (1990)
5. Shoemaker, D.P., C.W. Garland, J.I. Steinfeld, and J.W. Nibler, *Experiments in Physical Chemistry*, McGraw-Hill Publishing Co., New York, NY (1981) □

—CESL—

The Chemical Engineering Simulation Laboratory

DAVID A. KOFKE, MARC R. GROSSO, SREENIVAS GOLLAPUDI, CARL R.F. LUND
State University of New York at Buffalo • Buffalo, NY 14260-4200

Engineering and science *research* today are conducted within an emerging paradigm in which theory, experiment, and computer simulation play distinct but equally vital roles. Progress is often made in leapfrog fashion as each leg surmounts hurdles that have stalled the other two. Thus application of one technique never diminishes the role of the others, but rather enhances them.

The situation in the realm of science and engineering education is somewhat less advanced. Undergraduate instruction for decades has relied on a two-pronged approach of classroom and laboratory experiences. Classroom lectures convey concepts, while laboratory provides the students with physical experience—it exposes them to valves, gauges, flowing fluids, and generally, real-life operating equipment. Laboratory also teaches the students how to perform and analyze experiments, and well-designed laboratory exercises teach them how to plan experiments as well. Laboratories teach the limits of experiments, analysis of error, the importance of significant figures, and application of the models presented in the classroom.

Classroom and laboratory experiences are each irreplaceable

David A. Kofke is Associate Professor of Chemical Engineering at SUNY Buffalo. He earned his PhD in chemical engineering from the University of Pennsylvania and his BSChE from Carnegie-Mellon University. His research interests are in molecular thermodynamics.

Marc R. Grosso served as manager of the CESL project. He earned his PhD in Learning and Instruction from SUNY Buffalo in 1994. He also holds an MSE in Computer and Information Science from the University of Pennsylvania, a BS in Information Systems Management from Buffalo State College, and BSEd and MA degrees in Secondary Education. His professional interests are in the application of computing in instruction.

Sreenivas Gollapudi holds a MS in chemical engineering from SUNY Buffalo and is presently pursuing a MS in Computer Science. His BS degree in chemical engineering is from IIT Bombay. His research interests are parallel systems and multimedia.

Carl R.F. Lund is Associate Professor of Chemical Engineering at SUNY Buffalo. He earned his PhD in chemical engineering from the University of Wisconsin and his BSChE from Purdue University. His research interests are in catalysis and reaction engineering.

components of undergraduate engineering education. Nevertheless, they have shortcomings:

- *Space, safety, cost, and time considerations restrict the choice of laboratories*
- *Class sizes often preclude direct participation by students*
- *Laboratories must be maintained*
- *Class demonstrations are operated by the instructor*
- *It is difficult to make laboratory experiences substantially different for each student*
- *Lecture examples and homework often sample only a "small corner" of parameter space*
- *Laboratories are difficult to disseminate; the mere description of a well-designed lab does not suffice for someone else to implement it.*

A more fundamental drawback of the classroom and laboratory is their uncertain ability to instill physical *intuition* (as opposed to physical experience, which laboratory does well). Rarely is the laboratory a truly interactive exercise. The student conducts a series of pre-planned experiments and heads home to perform the analysis. This experience does not leave the students with an intuitive feel for the nature of the process. Likewise, classroom instruction is interactive in the sense of instructor-student, but it is not in the sense of student-process; classroom instruction is akin to teaching bicycling through the use of force and torque balances.

Shortcomings of the classroom and the laboratory can be alleviated through proper use of computer-based instruction. In chemical engineering, substantial progress has recently been made in this direction. A group at the University of Michigan^[1] has produced a set of tutorial modules that addresses topics across the chemical engineering curriculum. This we view as a valuable tool directed at the shortcomings of the classroom. Software that focuses on the laboratory also exists. In particular, a group at Purdue University^[2] has created a suite of modules that lets students perform pilot-

scale laboratories on the computer. Additionally, a host of packages has been developed for more specialized topics in chemical engineering, such as process control. Industrial simulation packages (*e.g.*, Hysim, Aspen) are used routinely and effectively, although this software has not been developed with an eye toward pedagogy. We feel that the potential of simulation as a tool for education is largely unfulfilled.

Indeed, the recent literature in engineering and science education journals has highlighted the tremendous potential of computers as a pedagogical tool, while at the same time lamenting the degree to which this potential is not being met. Seider^[3] (prior to the efforts at Michigan and Purdue) noted that in chemical engineering, instructional computing has kept pace with the profession only in the areas of process design and control. Many authors^[3-6] have noted two obstacles to the complete integration of computers within the engineering curriculum: the absence of powerful but inexpensive computers with strong graphics capabilities and the high cost (in terms of faculty time) of software development. The steady improvement of computing hardware has made the former a problem no longer. The latter obstacle is our target.

WHAT IS CESL?

At SUNY Buffalo we have developed a detailed plan and completed early development of software that enables education via simulation; we call our package CESL (pronounced "Cecil"). Seven department faculty have been active on this project (these include, in addition to two of the authors of this report, Scott Diamond, Johannes Nitsche, T.J. Mountziaris, Tom Weber, and Mike Ryan). CESL is designed to perform three functions:

- ▶ **It is an authoring tool**—CESL provides instructors with the ability to construct simulations with relative ease.
- ▶ **It is an environment for conducting simulations**—CESL permits the student to explore a process with a minimum of unnecessary effort.
- ▶ **It is an instruction and class management tool**—CESL allows the instructor to monitor, guide, record, and sometimes restrict the student's actions.

While all these features are inherent in its design, to date CESL has been developed only to a level that has permitted three prototype simulations to be implemented. In particular, many of the capabilities related to classroom use are designed but not yet coded.

SIMULATION

Once one considers simulation as part of the educational paradigm, one begins to realize how naturally and substantially it complements the laboratory and classroom experiences. As a simulator, CESL is much more than a simulated laboratory; it does more than just port the traditional lab to

Many authors^[3-6] have noted two obstacles to the complete integration of computers within the engineering curriculum: the absence of powerful but inexpensive computers with strong graphics capabilities and the high cost (in terms of faculty time) of software development. The steady improvement of computing hardware has made the former a problem no longer. The latter obstacle is our target.

the computer (although it can be used in that way too). There are obvious features such as time compression or expansion, a unique laboratory for each student, etc., enabled by simulation. But beyond this are more the pedagogical features of

- *Random events can be programmed to occur, to which the student must respond appropriately; less dramatic but just as useful, equipment can be programmed to "age" as it is used.*
- *Students can be quizzed in a number of ways, and their responses can be recorded; this can occur before, during, or after the simulation, and subsequent operation of the simulation can be based on their performance (*e.g.*, the student cannot begin until satisfactorily completing a pretest).*
- *Simulations can be conducted intermittently over several days, with the student being given a fixed period of time to return to the simulation; this time can be used by the student to reflect on subsequent actions.*
- *Access to a simulation can be restricted; likewise, the student may be given a fixed number of practice runs before conducting one or more runs for grading.*

No doubt many more novel features can be conceived. Our goal in developing CESL is to enable the simulation author to program and implement these features and the instructor to use them.

Clearly, there is great potential for diversity in design of simulations. It is helpful then to have an organizing principle when considering the options. We have identified the following four categories of simulation:

Laboratory • The student is presented with a piece of (virtual) equipment, or an entire process, and he or she conducts "experiments" on it to characterize its operation. This simulation is meant to mimic as closely as possible an actual laboratory experience; it is the mere simulated laboratory.

Steady-state simulation • The student must choose conditions that optimize the operation of some equipment when run at steady state. The parameters under which the simulation proceeds vary through the course of the experience, building an intuitive sense of cause-and-effect. The student is given a period of time (ranging from minutes to days, per simulation design) to reflect on each action.

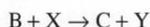
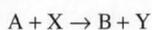
Unsteady-state simulation • The students operate equipment in “real” time (which may be compressed or expanded time, if needed). They must respond to regular or random changes in process operating conditions, relying mainly on an acquired intuitive “feel” for the equipment’s operation. Many actions are demanded of the student, each by itself being of small consequence, but together adding up to success or failure (perhaps catastrophic) in operating the equipment.

Design • The student is given equipment, or a budget with which to “purchase” equipment, and must assemble, test, and operate a process that is in some sense optimal.

Presently, only the first three categories of simulation can be constructed with CESL, and we have developed a prototype module for each: a simple tank-draining *laboratory*; a pump-sizing *steady-state* module; and an *unsteady-state* continuous stirred-tank reactor (CSTR) module. We will describe the last of these prototypes.

THE PROTOTYPE CSTR MODULE

The display for the prototype CSTR module is presented in Figure 1 (the actual display is in color). Series-parallel reactions take place within the reactor:



The reactions are exothermic and the reactor is not isothermal. Reactant X is presumed to be a gas that dissolves very rapidly in the liquid-phase reaction medium, so that the dissolved concentration of X is always proportional to its feed partial pressure (*i.e.*, Henry’s law is obeyed). Normally, the supply pressure of X is essentially constant (though there may be small fluctuations). The other reactant, A, is supplied from three tanks: one containing A in relatively high concentration, one containing A in “medium” concentration, and one containing A in “low” concentration. Deliveries are made at random times to replenish the three tanks.

The students must operate the system attempting to maximize the yield of the intermediate product, B. At the same time, they must prevent any of the tanks from overflowing and

must keep the reactor temperature under control. The students can manipulate the flow rate leaving each tank, the feed pressure of X (which must be less than or equal to the supply pressure), the flow of steam to the reactant pre-heater, and the flow of coolant to a coil within the reactor. A reactor quench can be used in an emergency if the student needs it. As already noted, the simulation will provide random deliveries to the feed tanks. The concentration and temperature in the tanks may fluctuate slightly due to these deliveries and seasonal conditions. Other potential problems that the simulation may invoke include a reduction in or loss of steam pressure for the pre-heater, a reduction in or loss of supply pressure of reactant X, a loss of cooling water flow or increase in cooling water temperature, and a gradual decrease in the heat transfer coefficients for the two exchangers. Because the reactions are exothermic, the student will need to exercise care whenever the feed concentration of reactant is increased or a thermal runaway may occur. Similarly, a large decrease in feed concentration may result in a significant temperature drop and thereby a loss of conversion.

The module is designed to develop within the students an intuitive feel for how conversion, yield, selectivity, and outlet temperature (call them response variables) are affected by changes in operating variables (feed composition, feed temperature, feed flow rate, and heat exchange) for series-parallel reaction networks. There are several stages or levels

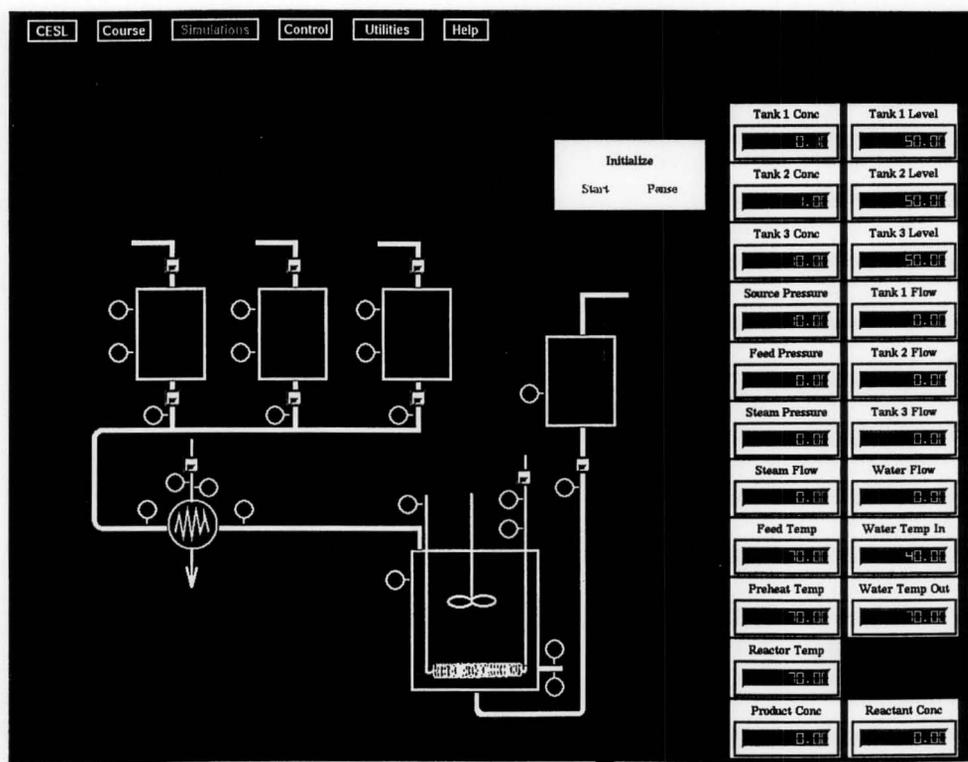


Figure 1. Display presented to student while operating CSTR prototype module. The actual display is in color.

of attaining such an intuition. The module allows the student to progress through these levels.

At the most elementary level, the student intuitively knows which operating variables to change and whether to increase or decrease them, in order to effect a specified change in one of the response variables. Often, a desired change can be brought about by manipulation of more than one variable. At the next level of intuition, the student knows which of the operating variables will be most effective in bringing about the desired response (*i.e.*, he or she knows which operating variable will cause the least change in the other response variables). At a yet higher level, the student knows how all the responses will change (at least direction and qualitative magnitude) when a given operating variable is changed.

At a still higher level of understanding, the student can explain why the system responds as it does to a given change in operating variables. Here the student should be able to formulate the explanation lucidly without the use of equations and mathematics. Finally, the ultimate objective of the module is that the student knows how all the above would differ if other parameters of the reactor were changed (*e.g.*, if the reaction was endothermic instead of exothermic, if the kinetic order of one or the other of the reactions increased or decreased, etc.).

OVERVIEW OF CESL DESIGN

A schematic of CESL and its role in the development and implementation of simulation laboratories is presented in Figure 2. In the upper-left corner of the figure is the process to be simulated; perhaps it is too large, dangerous, expensive, etc., to expose to the student. CESL comprises the elements within the gray-shaded region. The white-on-black components have not been implemented (or even designed) in the present version of CESL, but they will be developed as part of future work.

The simulation author is responsible for identifying the appropriate model for the physical system and for programming it using an established language (let us say that this is done in FORTRAN). We delegate this task to the module author for several reasons. First, quantitative modeling and programming form part of the undergraduate and graduate training of chemical engineers, so an instructor should have some competence here, at least for sufficiently simple experiments. Second, general and robust process simulators already exist, so any efforts expended by us in this direction would be inefficiently placed and thus detract from the important task of developing the novel features of CESL. Third, by making the model and simulation code separate from the core of CESL, we introduce a large element of flexibility in a

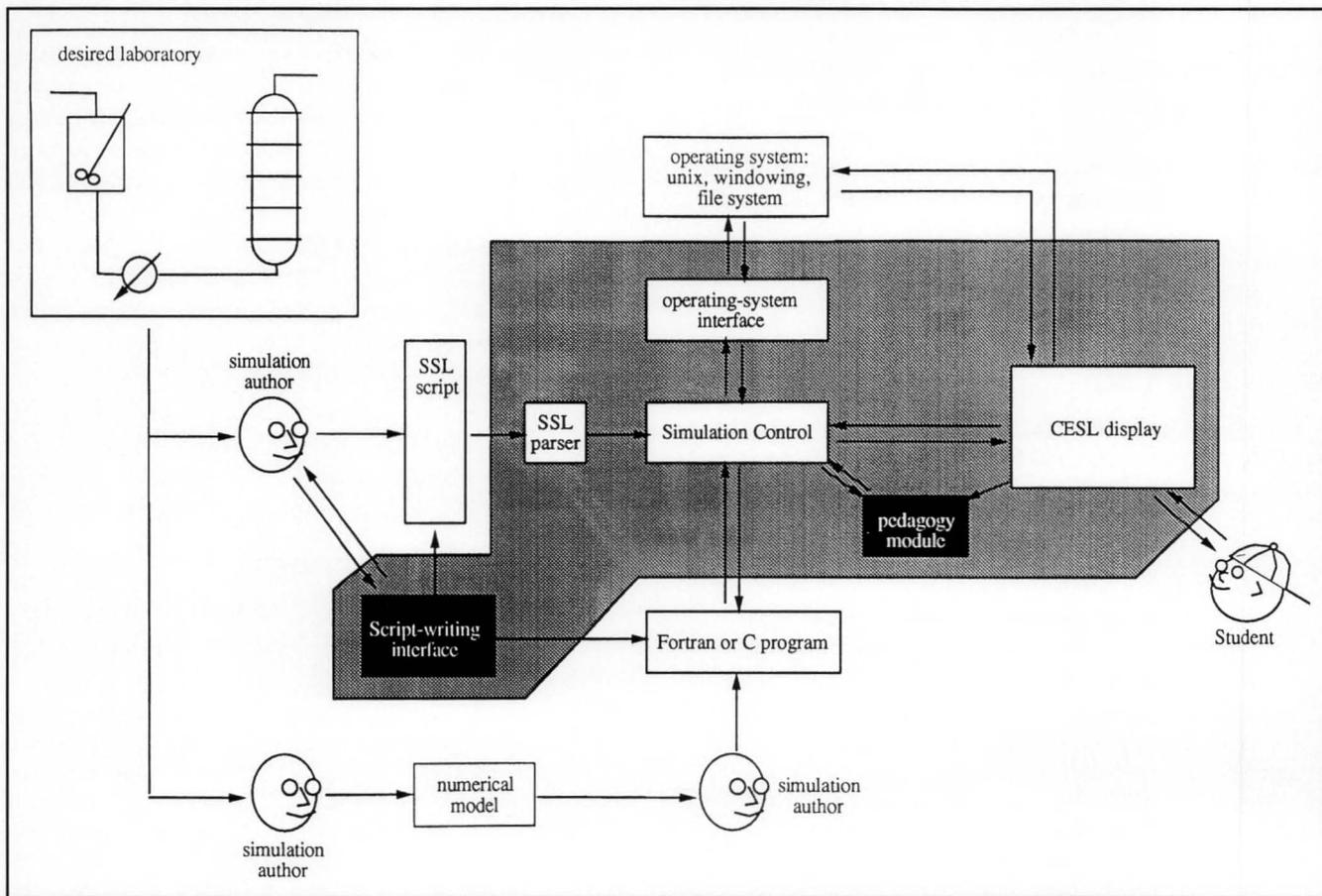


Figure 2. Schematic of simulation laboratory and CESL's role in implementing it.

module, and indeed in CESL itself. Instructors may modify or even replace the modeling code (presumably to improve it) while retaining the general simulation design and interface. More significant, extension of CESL to disciplines other than chemical engineering is well facilitated by this design.

The simulation author is also responsible for creating a graphical display through which the student interacts with the modeling code. Our goal has been to make this task as simple as possible. To this end, we have devised the *Simulation Script Language* (SSL), a declarative language through which the module author "equips the simulation" and specifies rules concerning how the equipment may be used and how it interacts with the numerical modeling code. The module author prepares the script using any text editor. The script is parsed by CESL when the student calls for the laboratory to be loaded into the system, and the "Simulation Control" element of CESL is thereby programmed with the laboratory. The Simulation Control element interfaces with the FORTRAN modeling program (to gather data and make sure that solution of the numerical model is proceeding synchronously with the wall clock), the operating system (e.g., to record data to file), and the CESL interface (through which the student conducts the simulation).

There are two elements presented in Figure 2 that were not needed to implement the prototypes but which are important to the ultimate success of CESL. First is a "pedagogy module," which monitors the activity of the student and reports to the Simulation Control the actions needed to improve the student's understanding of the lesson. Second is a script-writing interface. In simplest form, this interface will enable the author to prepare the SSL script using mouse-oriented actions; it will also guide the author in creating modules that are pedagogically sound. We plan to incorporate these features over the coming years.

MODULE WRITING

The SSL is a declarative language comprising a set of keywords and qualifiers that the module author uses to construct a simulation. Declarations may be categorized into the following three types:

Object statements declare "variables" and place corresponding graphical elements on the screen; these graphics can display or allow user-specified changes to the value of the variable. Simple examples include a temperature gauge or a valve that may be opened and shut.

Procedure statements declare the numerical routines that model the system's behavior. Included in these statements is a specification of the object-declared variables that are passed to the routine, and when or how often the routine is called. Routines may be called at fixed points in the experiment (e.g., immediately after the student initializes the laboratory), at regular intervals (of 0.1 sec, for example, if the routine is integrating unsteady equations in time), at random intervals

(to cause random events to which the student must respond), or at the behest of the student (by clicking on an appropriate graphic button). As programming the routines is completely up to the module author, they can make anything happen (e.g., a pressure loss is programmed by having the routine simply set the appropriate pressure variable to the newly desired value).

Controls declare restrictions and monitors of student's actions. The design and implementation of these features is in an early stage.

There are only two basic conceptual matters that a module author must grasp to construct a laboratory. The first deals with how CESL, the student, and the modeling routines change and communicate values of the laboratory parameters (e.g., temperatures, flow rates, status of valves). This is done using the "shared memory" concept. The idea is simple: there is one "official" repository of all parameter values, and they may be accessed or changed at any time by CESL, the student, or the modeling routines. Thus, once the modeling routine has computed a set of updated values (perhaps by completing a time-step calculation), it makes a simple call to a library routine that updates the shared-memory values.

The second conceptual matter concerns how CESL keeps in sync with the wall clock (an issue only with Laboratory and Unsteady-state simulations). The SSL script specifies how often a procedure is to update process variables. After computing its values, the routine suspends itself (again using a simple library call), until restarted by CESL (after a period of, say, 500 msec). When restarted, the values in shared memory may have been altered (e.g., a valve may have been shut off). When the routine next uses such values, it will produce results that reflect the changes. In particular, while the routine is suspended, CESL can update the "time variable" using the system clock. Thus the routine can be programmed to blindly update its variables to whatever time it reads from shared memory, without any concern about whether or how that time matches the wall clock.

The simple calls to routines that read and write shared memory, or suspend subroutine execution, are the only additions that the FORTRAN-routine author must include to interact with CESL. Everything else is familiar and standard.

PLANNED FEATURES OF CESL

CESL is a work in progress, and the following features have been designed in some detail but not yet incorporated in the software:

- ▶ *Experimental error may be introduced to an arbitrary extent and in two ways: the first is what we call "gauge error," and it describes the simple addition of normally distributed stochastic noise to the values reported to the student; the second is what we call "fluctuation," and it involves random perturbations to the process variables themselves. In contrast to gauge error, fluctuations are propagated through the system. They may in fact be viewed as part of the model that describes the*

physical behavior.

- ▶ Any process variable may be alarmed, with setpoints specified by the module author or the student, and with notification made audibly or via a visual indicator. It may prove interesting to observe which variables the students decide to alarm.
- ▶ Any process variable may be subject to automatic control using a PID 'device' that is tuned by the author or the student.
- ▶ The variability of the simulations is easily controlled; each student may be provided with a unique piece of equipment, or all students may be presented with the same equipment, or either of a pair of pieces of equipment, etc. Equipment may also be programmed to 'age,' with its operating characteristics changing in an appropriate way as it get older.
- ▶ The instructor may schedule the "availability" of the (virtual) equipment, restricting its use to, say, a particular one-week period. Also, the number of practice and grading runs may be specified, along with separate time periods for each.
- ▶ Data output by CESL for analysis by the student may be presented in any of several pre- or student-defined formats. The predefined formats are chosen to make them suitable for immediate input to popular graphing and analysis programs. This specification reflects a general design principle of CESL to exploit pre-existing software to the fullest extent possible. We do not wish to re-invent software that already exists and functions well.

Phillips,^[5] Koper,^[7] and Wankat and Oreovicz^[8] each emphasize the importance of the team approach to educational software development. Phillips notes the need for both curriculum and computer specialists on such a team, and Koper stresses the additional role of the educational technologist. In addition to the expertise offered by computer science majors and over half of our department's faculty, we have recently recruited to the project experts in education technology (Prof. Thomas Shuell of our Graduate School of Education) and human-computer interfaces (Prof. Valerie Shalin of our Department of Industrial Engineering). Their impact will be felt particularly in our subsequent efforts.

An interesting application of CESL concerns the development of new modules. We plan to offer to our students, in the form of an elective Projects course, the opportunity to develop new modules that could be used for instruction of subsequent classes. As part of this project, the student will be given the task of creating a working module. This will entail the concept for the module, considering carefully the instructional goal (provided by a faculty advisor), design of the module, writing of the script, programming the model, and testing the product. In this manner CESL will provide to the student a unique experience in pedagogy and design that simply could not be offered by other means.

DEVELOPMENT PLATFORM

We have chosen to develop our software on a Unix platform. We have been careful to employ development tools for which there exist industry standards. Thus all of our code is

written in ANSI-standard FORTRAN and (predominantly) C. We use the X-windowing system because it is widely portable and freely available. Because CESL itself interacts very well with the Unix operating system, we can readily introduce file-handling and classroom-management features that will underlie many of CESL's capabilities. This capacity also will facilitate the introduction of pedagogical functions that contribute to the realization of a complete computer-based instructional environment.^[9] For example, a record of student achievement and errors can be designed and maintained, allowing CESL's activities to be tailored to the student's progress.

Alternatives to our choice include the use of the C++ programming language and the traditional personal computer platforms. C++ is object-oriented and thus very well suited to our needs, so we are giving serious consideration to its eventual use. There is, however, no present ANSI standard for this language, and it is not as widely available or portable as C. The Macintosh and PC platforms are appealing because of their wide availability. These platforms are capable of running Unix and X-windows, so our present approach does not preclude porting to them.

ACKNOWLEDGMENTS

CESL was developed with the support of a Leadership in Laboratory Development grant from the National Science Foundation (DUE-9352500) and from the SUNY Buffalo School of Engineering. We wish to thank both Mr. Rich Alberth for very important contributions during CESL's formative stages and Dr. Nitin Ingle, who provided programming assistance to the project. Finally, we thank Sun Microsystems, Inc., for substantial equipment discounts and other support, and Mr. Corky Brunskill and his staff for their many contributions to our efforts.

REFERENCES

1. Fogler, H.S., and S. Montgomery, "Interactive Computer Modules for Chemical Engineering Instruction," *CACHE News*, **37**, 1 (1993)
2. Squires, R.G., G.V. Reklaitis, N.C. Yeh, J.F. Mosby, I.A. Karimi, and P.K. Andersen, "Purdue-Industry Computer Simulation Modules: The Amoco Resid Hydrotreater Process," *Chem. Eng. Ed.*, **25**, 98 (1991)
3. Seider, W., "Chemical Engineering Instruction and Computing: Are They in Step?" *Chem. Eng. Ed.*, **27**, 134 (1988)
4. Shacham, M., and M.B. Cutlip, "Authoring Systems for Laboratory Experiment Simulators," *Computers Educ.*, **12**, 277 (1988)
5. Phillips, W.A., "Individual Author Prototyping: Desktop Development of Courseware," *Computers Educ.*, **1**, 9 (1990)
6. Carnahan, B., "Computing in Engineering Education: From There, To Here, To Where?" *Chem. Eng. Ed.*, **25**, 218 (1991)
7. Koper, R., "Inscript: A Courseware Specification Language," *Computers Educ.*, **16**, 185 (1991)
8. Wankat, P.C., and F.S. Oreovicz, *Teaching Engineering*, McGraw-Hill, New York, NY (1993)
9. Wenger, E.L., *Artificial Intelligence and Tutoring Systems*, Morgan Kaufmann, Los Altos, CA (1987) □

ASEE ANNUAL MEETING

Washington, D.C.
June 23-26, 1996

Chemical Engineering Division Program

FEATURE SESSION

The Chemical Engineering Curriculum
#1213 - Is Anyone Out There Doing Anything Different?

Panelists:

- | | |
|------------------|-----------------|
| ◆ Harold Knickle | ◆ Mahbub Uddin |
| ◆ Barrie Jackson | ◆ James Watters |
| ◆ David DiBiasio | ◆ Andrew Wilson |

A panel discussion of current attempts to make sea changes in the total chemical engineering curriculum. Panelists will represent schools offering an alternative approach to delivering chemical engineering education. The discussion will focus on the rationale for each approach, good and bad experiences, student acceptance, and measures of success.

ADDITIONAL SESSIONS

- #1413 - Chemical Engineering Chairperson's Lunch
#3413 - Chemical Engineering Division Business Meeting and Lunch
#2613 - Chemical Engineering Division Award Lecture
#2713 - Chemical Engineering Division Dinner

REGULAR SESSIONS

#1613 *Innovative Uses for Educational Software Available Through CACHE*

- ▶ Employing the CACHE CD-ROM as an Educational Resource
- ▶ Facilitating Numerical Problem Solving With POLYMATH
- ▶ Picles™ for Bridging the Gap Between Laboratory and Textbook Learning
- ▶ Course Implementation of the Michigan PC Modules for Chemical Engineering

#2213 *Experimental Experience in the Undergraduate Curriculum*

- ▶ Integration of a Manufacturing Experience into the Undergraduate Curriculum in Polymer Engineering
- ▶ Implementation of Peer Feedback and Improvement Planning in the Unit Operations Laboratory
- ▶ Supercritical Fluid Extraction in the Undergraduate Laboratory
- ▶ Development of Multifunctional Laboratories in a New Engineering School
- ▶ Development of a Multidisciplinary Biochemical Engineering Laboratory
- ▶ Teaching Senior Unit Operations Laboratory Experiments to Engineering Freshmen

#2313 *Assessment of Learning Outcomes*

- ▶ Student Learning Assessment and the ABET Student Outcomes Criteria: Good News/ Bad News
- ▶ Project Gelegenheit: Skills Certifications Curricula for Engineering and Computer Science Disciplines
- ▶ A Portfolio-Based Assessment Program
- ▶ Outcomes Assessment Measures
- ▶ Assessment - Recent Regional Accreditation Experience

#2513 *Mentoring Graduate Students—Panel Session*

- ▶ Panelists: Richard C. Seagrave, Janice A. Phillips, Timothy J. Anderson, John P. O'Connell, and Jennifer Sinclair

#3213 *Homework Problem and Lecture Exchange*

- ▶ Exercises in Process Design for a Freshman Course in Chemical Engineering
- ▶ A Process Troubleshooting Program
- ▶ Entropy: Esoteric or Utility Infielder?
- ▶ Design of a Propylene Storage Facility
- ▶ Using Statistical Experimental Design to Optimize GC Operation
- ▶ Statistical Exercises in Chemical Engineering
- ▶ Teaching Data Analysis Techniques Using Practical Polymer Examples

#3513 *Technology Enhanced Instruction*

- ▶ Use of Computational Tools in Engineering Education
- ▶ Problem-Centered Course Objectives Leading to Multimedia Lessons
- ▶ Recent Developments in Virtual-Reality Based Education
- ▶ Controls Laboratory Teaching Via the World Wide Web
- ▶ Incorporating Bioengineering Examples into the Core ChE Courses

APPLIED STATISTICS

Are ChE Educators Meeting the Challenge?

(A Survey of Statistics in the Chemical Engineering Curricula)

ROGER E. ECKERT

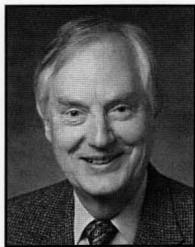
Purdue University • West Lafayette, IN 47907

W.A. Shewhart had a dream of a “statistically minded generation” (W. E. Deming, 1939^[1]). This dream exists today, says R.G. Batson,^[2] “but, as we are all keenly aware, not in the U.S.”

For years, industry has recognized the need for chemical engineers to understand and use applied statistics. Increasingly stringent quality requirements and emphasis on TQM (Total Quality Management) have intensified this need in recent years. Probably more in-house courses on statistics-related topics are given to engineers in industry than on any other technical subject. Since at least the 1960s, surveys of engineers and managers in industry have repeatedly shown a shortfall in this area.^[3] What are chemical engineering educators doing to correct this deficiency? Will we relinquish our job of educating chemical engineers in such an important area?

ABET has added the accreditation criterion, “Students must demonstrate knowledge of the application of probability and statistics to engineering problems” (Sec. IV.C.3.h). What evidence will educators present to a visiting team during ABET accreditation that graduates meet this criterion? Chemical engineering students take mathematics courses through differential equations, but do they have even an introduction to the random variable and stochastic processes? Even more important, are they sufficiently prepared to use statistics correctly and efficiently in their industrial careers? Or will the industrial emphasis on TQM be a surprise and a stumbling block for the new graduate?

Roger E. Eckert is a professor of chemical engineering at Purdue University. He received his BS in chemical engineering at Princeton University and his MS and PhD at the University of Illinois, joining DuPont after graduation. After over a decade of industrial research and development, he moved to Purdue, where he has taught and researched applied statistics and experimental design, multiphase reactions, and polymers.



© Copyright ChE Division of ASEE 1996

The survey that forms the basis of this article was sent to 172 chemical engineering departments in the United States and Canada and was devised to develop information on the status of applied statistics as background for educators and industry to view our progress toward the above goals. The purpose of the survey was not to establish the “ideal course” or sequence, but to stimulate thought and discussion in this direction. It is, to the best of our knowledge, the first survey on the extent to which statistics is included in the chemical engineering curriculum.

The questionnaire was sent as a single-page attachment to the annual course survey by the Chemical Engineering Education Projects Committee of AIChE in April of 1993 and was conducted by the late Edwin Eisen (McNeese State University). A follow-up request from John Griffith was sent to non-respondents in August, and forms continued to be returned in 1994. Inquiries were made about the status of inclusion of the usual topics of applied statistics. The important related subjects of experimental design and quality control were added.

THE SURVEY

The purpose of this survey was to present a summary of the status of statistics-related education in chemical engineering. The questions asked were

ABET has added the requirement “Students must demonstrate knowledge of the applications of probability and statistics to engineering problems.” Are these topics included in your required curriculum? Are you planning curriculum changes on this topic? Are elective courses including these topics taken by some of the chemical engineering students?

In addition to responses to the above questions, information about the courses (*e.g.*, is the course required, the department that offers the course, coverage of the field, and the textbooks used) was requested, and this information is summarized along with responses to the above questions.

RESPONSES

Of the 112 departments that replied to the survey (65% returned), all but five provided usable information for analysis. Eighty-six (80%) reported that topics pertaining to the ABET criterion are included in their required curriculum; 21 (20%) said no such topics are required. Therefore, most chemical engineering curricula require some statistics either as a separate course or as part of a course.

Note that the survey was sent to the entire population of chemical engineering departments and not simply to a sample selection. Therefore, there are no confidence intervals or "margins of error." The 60 non-responding departments (35%), however, are not expected to parallel the results presented here. Without direct substantiation, the author believes departments that do not have applied statistics in their curricula were less likely to respond to the survey. An absolute lower limit on the percentage of schools that include such topics is obtained from the positive replies out of the questionnaires sent, which is 50%, in comparison with 80% of the actual responses.

The question "Are you planning curriculum changes on this topic?" resulted in 31% "yes" responses from the participating schools. Percentages of the 107 useful responses are presented in tabular form for accuracy in Figure 1. These results, along with the 80% including statistics in the curriculum noted above are shown on the 3-D bar graph in Figure 1. The rectangle heights represent percentages of the useful 107 responses. Please refer to the "Total" columns

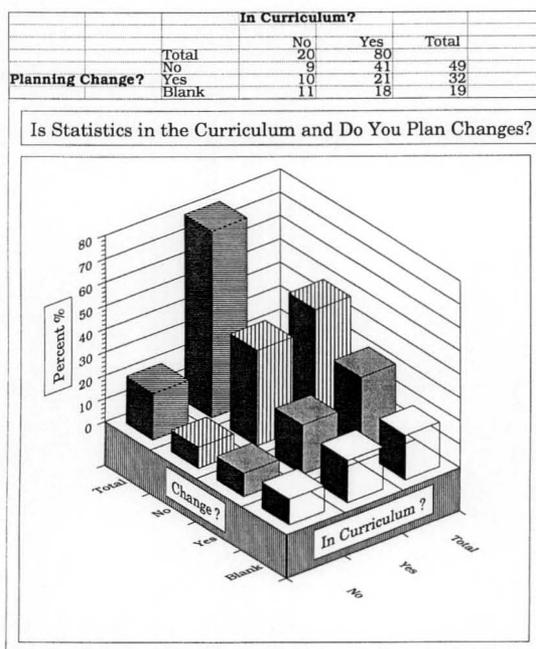


Figure 1. Percentages of the total 107 survey responses to the two questions "Are statistical topics included in your required curriculum?" and "Are you planning curriculum changes on this topic?"

Spring 1996

first on each question; these are the tallest bars at the rear for each axis. The 100% grand total that would appear in the rear corner is purposely omitted to better display the important results. You will first see the 80-20% response to the "In Curriculum?" question. On the question of changes to the curriculum, 18% of the responses were blank, but all these respondents did answer the requirement question. Then, as lower limits, 31% plan to make changes and 51% do not. As expected, these two responses interact. For those with a requirement, only one-third are planning changes (21% yes; 42% no), while about half of those with no requirement plan changes (10% yes; 9% no).

Of the 80% that require statistics in the curriculum, 42% have a major course on this topic (see Figure 2). Major course coverage is defined as greater than one credit hour of statistics that includes four or more of the seven topics listed in Table 1. Slightly more, 45%, include statistics in a course and do not have the coverage defined for major coverage.

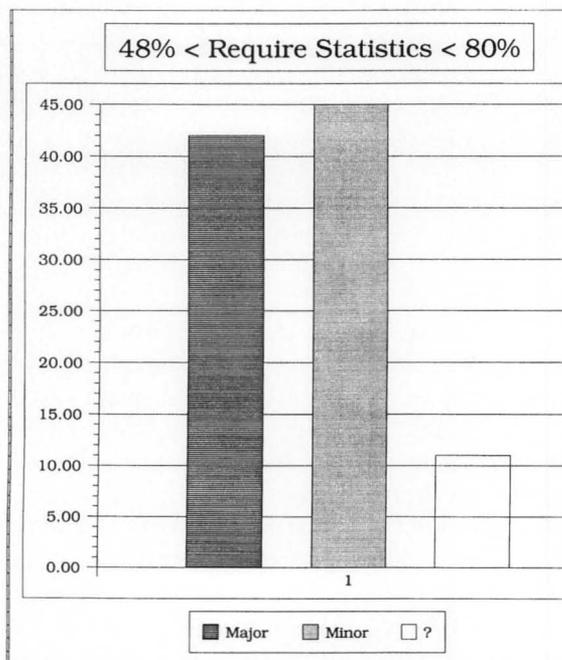


Figure 2. For those schools that require statistical topics, the percentage that require a major amount of a course (greater than 1 credit hour and more than 3 topics from Table 1) or a minor amount are compared. If it was not possible to make this decision based on the information supplied, the school was counted in the (?) bar.

TABLE 1
Statistics Related Topics Listed on the Questionnaire
(Submitter noted if topic is in each course.)

- Distributions
- Statistics, t , χ^2 , F
- Regression Modeling
- Analysis of Variance
- Design of Experiments
- Quality Control
- Other (as needed)

Some (11%) report a course but did not provide sufficient detail to make this determination.

Figure 3 is a bar chart and table of detailed breakdown percentages for those departments that require a major course. Sixty percent place it in the junior year, and the rest are equally divided between the sophomore and senior years. No "major" course coverage, as defined above, was reported for the freshman year. The majority of these courses (57%) are offered by the chemical engineering departments. About a third of the courses are from mathematics or statistics departments, and the remaining 9% are offered by other engineering departments, mostly industrial engineering. The math/stat courses are concentrated even more heavily in the junior year; the number is close to that given by chemical engineering departments in the junior year.

When only a smaller part of a required course is statistics (see Figure 4), the courses reported are all taught within chemical engineering but are divided between class (58%) and laboratory (42%). More of the classes are in the sophomore and junior years. Few are during the freshman year, and an intermediate number are in the senior year. The laboratory courses are, of course, heavily concentrated in the senior year, with less than one-third of the labs in the junior year. Overall, there is a progression of increasing numbers of courses toward the end of the curriculum. Application of the content to other courses is thus limited.

STATISTICS ELECTIVES

Suitable applied statistics elective course(s) that some chemical engineering students take were reported by 86% of the departments responding to the questionnaire. Figure 5 includes the "blank" responses, so 78% is the corresponding figure. Surprisingly, whether or not statistics is required in the curriculum, about the same percentage of departments report some chemical engineering students take statistics electives. Perhaps the students' need for statistics when none is required is balanced by further interest in electives when the subject is required. Furthermore, whether or not some chemical engineering students take a statistics elective does not affect the school's decision to change the curriculum. The regularity of the response bars indicating no interaction to these two questions can be noted in Figure 5. The elective response is totally independent of the other two "yes and no" questions of Figure 1. For this reason, electives were analyzed separately.

The number of chemical engineering students who elect such a course was not asked on this survey since a detailed study of student records would have been required to determine the percentage of students who take such an elective. Not even a single remark to the effect that many or most of the chemical engineers take these electives was offered on the survey sheets. We might infer that the number of chemical engineers introduced to statistics

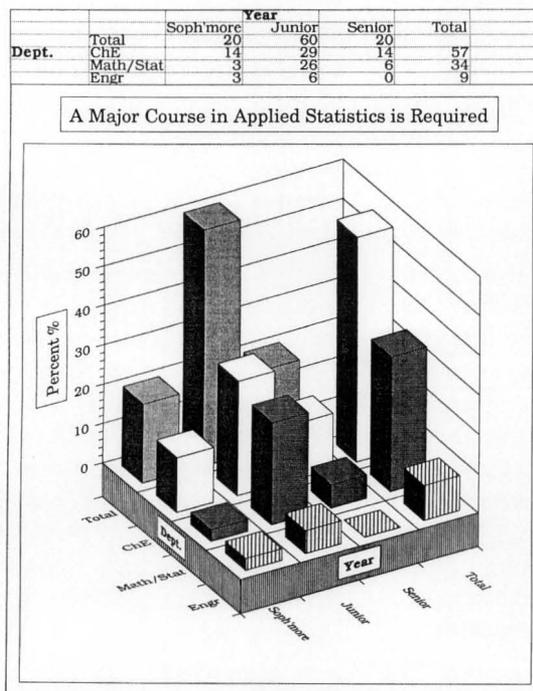


Figure 3. The percentage of schools requiring a course with major amount of statistics is displayed by the combination of the department offering the course and the year in which students normally take the course.

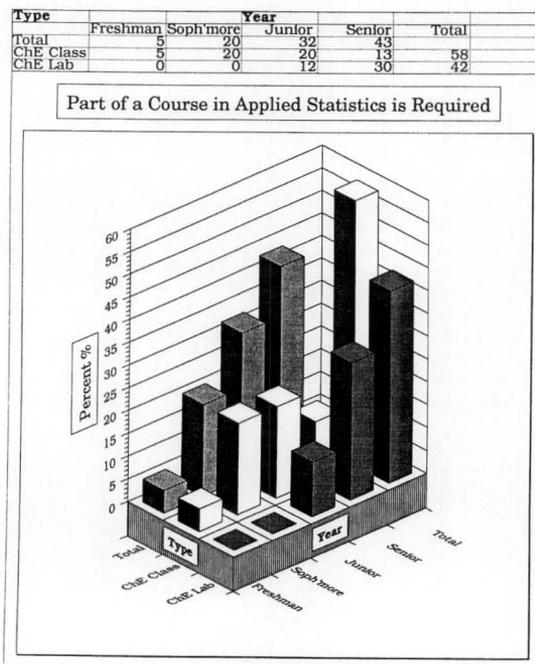


Figure 4. When the schools require less statistics than that defined as major in Figure 2, statistics is often included with a chemical engineering laboratory course. Alternatively, statistics is included with a "class," which is a lecture and/or recitation. The percentage of each of these and the year in which students normally take the course is displayed.

through an elective course is low.

Elective courses that have a major emphasis on statistics are offered in sixteen chemical engineering departments. Twelve of these courses include six or all seven of the topics listed in Table 1. The topics most often *not* included from this list are the applied topics of experimental design and quality control. Although these are useful topics, they usually follow more basic statistics in a course. Other topics of a statistical nature that were noted by the respondents are propagation of error, time series, nonparametric analysis, maximum likelihood, uncertainty analysis, and SPC. Also noted were several software packages such as SAS, Minitab, and Matlab.

TEXTBOOKS

The response to the request that the text be listed was both disappointing and revealing. It had been expected that texts for courses outside chemical engineering would often not be known by the supplier of this information, but even within chemical engineering only a few texts were listed, and there was no predominant one. The five mentioned more than one time are

- *Box, G.E.P., W.G. Hunter, and J.S. Hunter, Statistics for Experimenters, Wiley, New York, NY (1978)*
- *Devore, Jay L., Probability and Statistics for Engineering and the Sciences, 3rd ed., Brooks/Cole, Monterey, CA (1991)*
- *Hogg, R.V., and J. Ledolter, Engineering Statistics, 2nd ed., Macmillan (1992)*
- *Mason, R.L., R.F. Gunst, and J.L. Hess, Statistical Design*

and Analysis of Experiments: With Applications to Engineering and Science, Wiley, New York, NY (1989)

- *Walpole, R.E., and R.H. Myers, Probability and Statistics for Engineers and Scientists, 3rd ed., Macmillan (1985)*

It should be noted that several new texts with titles that included "statistics for engineers" have been published since the start of this survey.

CONCLUSIONS

Over half of the chemical engineering curricula has at least some applied statistics in required courses. Many departments are adding statistics to required courses and are currently changing their curriculum in this regard. It will be necessary for others to include this general topic to meet the new ABET criteria. The required extent of coverage will undoubtedly depend much on the specific accreditor(s)' interpretation as this requirement is enforced through the coming years.

A preferred approach, whether the curriculum now includes applied statistics or not, is to look to the needs of the graduate chemical engineer. With computers in universal use, the extensive calculations to apply statistics can be readily performed. Good experimental design is essential for the efficiency and productivity demanded in today's markets. There is an elusive optimum range for the amount of applied statistics in the chemical engineering curriculum. In achieving these goals, decisions will be necessary on what portion of the current curricula will be supplemented or supplanted. A single course, with material carefully selected for maximum application both in the curriculum and in industry, will likely be the minimum need.

An early introduction to stochastic variables in mathematics courses would help to "pave the way" toward engineering applications courses. Elective courses will continue to increase the availability of these topics to the interested student, but they are not a substitute for a minimum requirement for understanding of statistics of the stochastic variable in parallel with mathematics of the deterministic variable.

ACKNOWLEDGMENT

Edwin Eisen kindly offered to include the questionnaire with his annual survey of courses. After his death, D. John Griffith continued the work and I am indebted to them for such help. I also thank the 107 professors who completed the questionnaires that provided the data for this paper.

REFERENCES

1. Deming, W.E., Shewhart, W.A., *Statistical Method from the Viewpoint of Quality Control*, Dept. of Agriculture, Washington, DC (1939)
2. Batson, R.G., "Statistical Training: A National Necessity," *Eng. Ed.*, Sept/Oct, 598 (1989)
3. "Two Surveys Show: What Engineers Would Study," *Engineer* (Engineers Joint Council), 6(2), Summer/Fall, 4 (1965) □

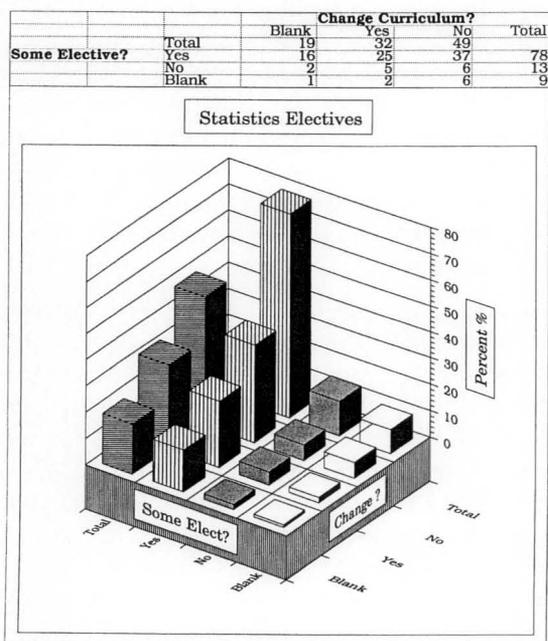


Figure 5. Whether or not some chemical engineering engineering students elect statistics-related courses does not affect the department's decision to make curriculum changes regarding statistics.

This column provides examples of cases in which students have gained knowledge, insight, and experience in the practice of chemical engineering while in an industrial setting. Summer interns and coop assignments typify such experiences; however, reports of more unusual cases are also welcome. Description of analytical tools used and the skills developed during the project should be emphasized. These examples should stimulate innovative approaches to bring real world tools and experiences back to campus for integration into the curriculum. Please submit manuscripts to Professor W. J. Koros, Chemical Engineering Department, University of Texas, Austin, Texas 78712.

INTERNATIONAL ENGINEERING INTERNSHIP PROGRAM *At The University of Rhode Island*

JOHN M. GRANDIN, KRISTEN L. VERDUCHI*
University of Rhode Island • Kingston, RI 02881-0805

Through the cooperative efforts of engineering and foreign language faculty, the University of Rhode Island (URI) offers a five-year International Engineering Program (IEP) that leads simultaneously to both the Bachelor of Arts degree with a major in German and the Bachelor of Science degree in one of the engineering disciplines. Key features of the IEP include separate sections of German language courses specially designed for engineering students, a six-month internship with an engineering firm in a German-speaking country, and a capstone engineering course taught in German by bilingual engineering faculty. In many cases, IEP students also complete internships with IEP partner companies in the Rhode Island area

John M. Grandin is Professor of German, Chair of the Department of Languages, and Director of the International Engineering Program at the University of Rhode Island. He holds a PhD from the University of Michigan. In recent years he has spoken and published widely on the internationalization of engineering education.

Kristen L. Verduchi is a Process Engineer at the Hoechst Celanese Corporation in Coventry, Rhode Island. She graduated in 1994 from the International Engineering Program at the University of Rhode Island with a Bachelor of Science in chemical engineering and the Bachelor of Arts in German.

* Address: Hoechst Celanese Corporation • Coventry, Rhode Island

before commencing the European internship experience in the fourth year of the program.

The program was begun eight years ago with the help of a grant from the Fund for the Improvement of Post Secondary Education (U.S. Department of Education). Since that time, over fifty students have completed their six-month internships abroad, and approximately thirty-five students have graduated from the University with both degrees, several of whom have gone to work for the companies participating in the internship program. The successes of the IEP have led to a growing popularity of the program, which now boasts an enrollment of over eighty students.

The internship program in Germany is a key element to the success of the IEP. The concept serves first of all as a motivator for students to study Germanic language and culture along with their engineering studies. Above all, the internship is the experience that puts study into practice and provides concrete experience for students who plan to practice their careers in a cross-cultural environment. Although arrangements are made in advance for the students by the program's director, expectations on-site are the same as they would be for German students. All work is intended to draw on their engineering background and is carried out exclusively in the German language. The goals are to experience engineering as it is practiced in Germany and to refine

German language and intercultural communication skills, *i.e.*, to put their seven semesters of engineering and language study into practice in a very real situation.

The program was developed through a variety of contacts, many of which have been facilitated through the efforts of the IEP Advisory Board members, a group of Rhode Islanders active in various aspects of international business and technology. Internship opportunities in Germany are maintained with approximately twenty companies through annual visits abroad and through various forms of communication, including mail, telephone, fax, and e-mail. Some companies are subsidiaries or partners of Rhode Island-based American firms; some are the home bases of German subsidiaries in Rhode Island; others are firms that have come to our attention through our earliest contacts in Germany. In each case, the companies agree to provide an organized engineering work experience and both housing and a subsistence-level monthly stipend for the IEP interns. In general, arrangements are made approximately six months in advance in order to ensure enough time for proper arrangements, including the necessary visa and work permit.

As of this year, the program also includes an optional study abroad component. With the support of a grant from FIPSE, URI business, engineering, and language faculty have worked closely with their counterparts at the Technische Universität Braunschweig to develop a one-to-one student exchange through which students may study in their field of expertise at the partner school with full accreditation at the home institution. Five IEP students are in Braunschweig this academic year, some of whom are planning a semester of study and a six-month internship at one of our partner companies. At the same time, five Braunschweig students are currently in Rhode Island pursuing their engineering studies at the advanced undergraduate and graduate levels.

It is important to stress that the program is a full double-degree program that satisfies all requirements for both the Bachelor of Arts and the Bachelor of Science degrees. Several attempts have been made at other institutions to internationalize the engineering curriculum through the addition of a few relevant courses or an intensive summer seminar. URI takes the position, however, that this challenge can only be met through a commitment of additional time at the undergraduate level. Students in the program are expected to take a German language or culture course each semester throughout the five years. They are not recommended for an internship abroad until they have completed at least six semesters of German along with at least three years of their technical studies. The companies in Germany are eager to have young American engineering students participate in their internship programs, but only when they are able to communicate in German and contribute to their technical needs.

URI views its program with a German orientation as a successfully developed model that is equally appropriate for other languages and cultures. German was chosen for the pilot program because of the level of commitment on the German faculty and the presence of several German-speaking faculty in the College of Engineering. URI is currently working on the development of a parallel program in French and is also studying the feasibility of a similar program in Spanish that would serve the needs of Spanish-speaking immigrants in Rhode Island.

Chemical engineering majors in the URI program have an excellent

. . . [the program] leads simultaneously to both the Bachelor of Arts degree with a major in German and the Bachelor of Science degree in one of the engineering disciplines. Key features . . . include separate sections of German language courses specially designed for engineering students, a six-month internship with an engineering firm in a German-speaking country, and a capstone engineering course taught in German by bilingual engineering faculty. . . . Above all, the internship is the experience that puts study into practice and provides concrete experience for students who plan to practice their careers in a cross-cultural environment.

opportunity for both U.S. and German internships since the program is strongly endorsed by a local division of the Hoechst Celanese Corporation. Seven IEP students have completed internships with the Hoechst headquarters in Germany, most of whom had the opportunity to work with Hoechst in Rhode Island in advance of the German experience and five of whom subsequently joined Hoechst Celanese on a permanent basis after graduation. Ms. Kristen Verduchi, one of these five students and now a process engineer with this company, offers the following overview of her IEP education at URI:

In May of 1994, I completed the International Engineering Program at the University of Rhode Island following my return from a six-month internship at the headquarters of Hoechst AG in Frankfurt, Germany. The five-year IEP consists of nine semesters with an average of 17 to 19 credits/semester of university study and six months of an internship in Germany. A semester during the fourth or fifth year is spent abroad gaining practical experience at an engineering firm in Germany. The university's program of study provides the theoretical knowledge in the classroom and the internship provides the opportunity to put the engineering knowledge into practice. In this way, the International Engineering Program is not only a novel way to imbue an engineering curriculum with international flavor, but also a way for students to put the classroom theory into practice.

The undergraduates who plan to undertake the dual degree IEP must decide to do so early in their college careers, for one must complete approximately four years of the IEP curriculum prior to traveling to Germany for an internship at an engineering firm. Declaring participation in the program early also has the advantage of making the student eligible to intern at a Rhode Island engineering firm in his/her field prior to going to Germany. It is this opportunity and subsequent ones that I will describe here.

My summer assignment following completion of the first year of the undergraduate IEP was an internship at Hoechst Celanese Corporation in Coventry, Rhode Island. I worked during the summers of 1990-92 as an engineering intern in the Process Engineering Department, carrying out projects such as those listed below, each of which provided me with practical skills and hands-on training not taught in the classroom:

- *Investigation of the composition of a waste-air stack from pharmaceuticals' processes using a Fourier Transform Infrared instrument and development of a user manual.*
- *Survey of plantwide lighting for the Narragansett Electric Efficiency Program.*

- *Development of piping and instrumentation diagrams of pharmaceuticals' processes and of plantwide steam and condensate lines.*
- *Study of pressure relief devices.*

Following completion of the fourth year of study, I applied through the URI program to Hoechst AG in Frankfurt am Main, Germany, for a professional internship. Between June and December of 1993, I interned in the Process Engineering Department in Environmental Engineering at Hoechst AG. In this extraordinarily diverse work environment and culture, I experienced a new lifestyle and adapted to new customs and to a new style of communication.

New friends from various parts of the world as well as professional relations with the employees from Hoechst AG were among the many benefits of the internship. Understanding and respect for the German culture (or any foreign culture) is the key to successful relations in professional and personal German life. One must not be overcome by culture shock, but must accept the foreign culture with an open mind, must be willing to attempt new things, and must modify one's thinking patterns. Success in a foreign work environment is representative of how well-suited one is to change and therefore to success in the constantly changing world. It was with this mode of thinking that I was able to learn about environmental engineering from the chemists and technical assistants at Hoechst AG in Frankfurt.

For the six months between June and December of 1993,

TABLE 1
Source Material on the
International Engineering Program
John M. Grandin, Author

- "German and Engineering: An Overdue Alliance," *Die Unterrichtspraxis*, **22**, 146-152 (1989)
- "Deutsch Für Ingenieure: Das Rhode Island Programm," in *Das Jahrbuch Deutsch als Fremdsprache*, **15**, 297-306 (1989)
- "Developing Internships in Germany for International Engineering Students," *Die Unterrichtspraxis*, **2**, 209-214 (1991)
- "The Changing Goals of Language Instruction," (with Kandace Einbeck and Walter von Reinhardt) in *Languages for a Multicultural World in Transition*, ed. Heidi Byrnes (Lincolnwood, Illinois: National Textbook Company and Northeast Conference) 123-163 (1992)
- "International Experience for Engineers," (with H. Viets), in *The International Journal of Engineering Education*, **9**(1), 93-94 (1993)
- "The University of Rhode Island's International Engineering Program," in *Language and Content: Discipline and Content-Based Approaches to Language Study*, ed. Merle Krueger and Frank Ryan (Lexington, Massachusetts: D.C. Heath and Company), 130-137 (1992)

CALL FOR PAPERS

Fall 1996 Graduate Education Issue of *Chemical Engineering Education*

Each year CEE publishes a special fall issue devoted to graduate education. It includes articles on graduate courses and research as well as ads describing university graduate programs.

Anyone interested in contributing to the editorial content of the 1996 fall issue should write to CEE, indicating the subject of the contribution and the tentative date it will be submitted.

Deadline is July 1, 1996.

I conducted study, design, and testing on an experimental absorption facility in a laboratory. There, I designed a laboratory-scale test facility and investigated the absorption capabilities of several packings used to purify a waste-air stream using infrared spectroscopy. The experimental and theoretical results of the design, testing, and analysis were documented and distributed to Hoechst AG for review and to URI for academic credit. The report submitted to the language and chemical engineering departments (in both English and German) earned me two additional credits toward the language degree, in addition to the six credits awarded for the internship abroad. It was this report that was later submitted to and presented at the 1994 American Institute of Chemical Engineers' paper contest during my last year at URI.

I am grateful to URI and to the creators of the IEP for establishing such a fantastic undergraduate curriculum that affords engineering students the opportunity to study and work in an engineering field in Germany. The industry needs engineering students who are bilingual, for we are entering a time when global competition in business demands international ties, relationships, and communication. The IEP trains engineering students for the global marketplace.

Subsequent to the internships at Hoechst Celanese Corporation in Coventry and following the six-month internship in Frankfurt, I applied to Hoechst Celanese Corporation in Coventry for a permanent position as a process engineer/process safety engineer—I joined the company in that capacity in June of 1994. I felt that my educational background and internship experience in chemical engineering with both the home and the parent companies corresponded quite well with the job requirements. Since I joined the company, I have greatly enjoyed

the challenging work in the process engineering/process safety position and can report that the dual degree has provided me with important tools. I find myself conversing in German quite regularly with native Germans assigned to our facility and with visitors from Germany. In addition, I provide the service of translating technical documents from Germany for process engineers.

Although Hoechst Celanese plays a major role in the practical education of chemical engineering students in the IEP, it is not the only regional firm cooperating with the URI program. Several students have also worked in a parallel manner, for example, with a division of TRW in nearby Massachusetts. To date, TRW has employed several chemical engineering students from the program in local summer internship situations, three of whom have completed six-month internships with TRW subsidiaries in Germany. Among the four IEP grads who have gone to work full-time for TRW, two are chemical engineers with assignments in materials engineering and airbag deployment technology.

URI and its partners in the private sector take pride in the development of the IEP as a model for the global education of young engineers. Engineering educators are challenged to prepare students for the international nature of their fields today and also for the contemporary needs of research, design, and manufacturing. URI believes that the best response to these challenges is through genuine interdisciplinary cooperation within the structure of higher education, e.g., engineering and language, as well as through carefully coordinated partnerships between higher education and those companies who will be employing our future graduates.

Additional source material on the International Engineering Program is presented in Table 1 for those readers who are interested in further information. □

Random Thoughts . . .

SPEAKING OF EVERYTHING

RICHARD M. FELDER

North Carolina State University • Raleigh, NC 27695

- ❶ *A rock pile ceases to be a rock pile the moment a single man contemplates it, bearing within him the image of a cathedral.*
_____ Antoine de Sant Exupère
- ❷ *Whenever things get really bad, there is always some one to assure us amid great applause that nothing has happened and everything is in order.*
_____ Carl Jung
- ❸ *Children have never been very good at listening to their elders, but they have never failed to imitate them.*
_____ James Baldwin
- ❹ *We get the best results in education and research if we leave their management to people who know something about them.*
_____ Robert Hutchins
- ❺ *Every man is a damn fool for at least five minutes every day. Wisdom consists in not exceeding the limit.*
_____ Elbert Hubbard
- ❻ *Law of Probable Dispersal: Whatever hits the fan will not be evenly distributed.*
_____ Anonymous
- ❼ *A man's hatred is always concentrated on the thing that makes him conscious of his bad qualities.*
_____ Carl Jung
- ❽ *There is something that is much more scarce, something rarer than ability. It is the ability to recognize ability.*
_____ Robert Half



Richard M. Felder is Hoechst Celanese Professor of Chemical Engineering at North Carolina State University. He received his BChE from City College of CUNY and his PhD from Princeton. He has presented courses on chemical engineering principles, reactor design, process optimization, and effective teaching to various American and foreign industries and institutions. He is coauthor of the text *Elementary Principles of Chemical Processes* (Wiley, 1986).

© Copyright ChE Division of ASEE 1996

- ❶ *Never attribute to malice that which is adequately explained by stupidity.*
 _____ Fred Vorhis
- ❷ *Expertise in one field does not carry over into other fields. But experts often think so. The narrower their field of knowledge the more likely they are to think so.*
 _____ Robert Heinlein
- ❸ *Many men stumble over discoveries, but most of them pick themselves up and walk away.*
 _____ Winston Churchill
- ❹ *Experience is a hard teacher because she gives the test first, the lesson afterwards.*
 _____ Vernon Law
- ❺ *The only reason I would take up jogging is to hear heavy breathing again.*
 _____ Erma Bombeck
- ❻ *Among those whom I like or admire, I can find no common denominator, but among those I love I can: all of them make me laugh.*
 _____ W. H. Auden
- ❼ *La causa de lo que hacemos es lo que creemos y también lo que buscamos.*
 _____ Armando Rugarcia
- ❽ *Creativity always dies a quick death in rooms that house conference tables.*
 _____ Bruce Herschensoln
- ❾ *I write when I'm inspired, and I see to it that I'm inspired at nine o'clock every morning.*
 _____ Peter DeVries
- ❿ *I believe in miracles in every area of life except writing. Experience has shown me that there are no miracles in writing. The only thing that produces good writing is hard work.*
 _____ Isaac Bashevis Singer
- ⓫ *We are so constituted that we believe the most incredible things, and once they are engraved upon the memory, woe to him that would endeavor to erase them.*
 _____ Goethe
- ⓬ *Good judgment comes from experience. Experience comes from bad judgment.*
 _____ Anonymous
- ⓭ *Our achievements speak for themselves. What we have to keep track of are our failures, discouragements, and doubts. We tend to forget the past difficulties, the many false starts, and the painful groping. We see our past achievements as the end result of a clean forward thrust, and our present difficulties as signs of decline and decay.*
 _____ Eric Hoffer
- ⓮ *More than any other time in history, mankind faces the crossroads. One path leads to despair and utter hopelessness, the other to total extinction. I pray we have the wisdom to choose wisely.*
 _____ Woody Allen
- ⓯ *I never forget a face, but in your case I'll make an exception.*
 _____ Groucho Marx

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

DYNAMIC AND STEADY-STATE BEHAVIOR OF A CSTR

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

Mathematical models describe real systems in terms of a set of mathematical equations (differential or algebraic). This representation of the physical and chemical phenomena governing the system, along with the analytical and/or numerical solutions developed, enables us to predict the dynamic and/or steady-state behavior of this system. Analytical solutions are usually the most satisfactory, but they become difficult with increasingly complex systems. Numerical solutions are useful when analytical solutions cannot be obtained or when comparison with the available analytical solution is required to confirm the correctness of the latter.

Abu-Khalaf^[1] described a reactor setup (see Figure 1) where a second-order reaction was studied with equimolar feed concentrations and equal flow rates of the reactants under isothermal conditions. Three stages of the CSTR were modeled, namely from beginning to overflow (e.g., while the reactor is filling up to a constant volume), from overflow to the approach to steady state, and the final steady-state

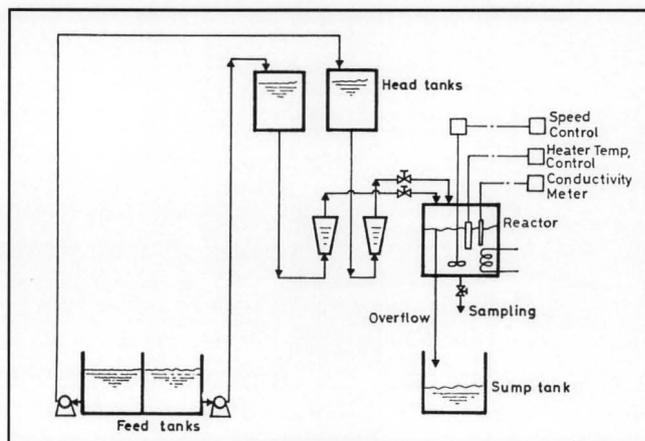
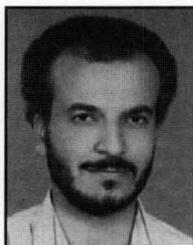


Figure 1. Reactor setup.

operation. Mathematical models with both analytical and numerical solutions were developed. The mathematics involved, however, is rather advanced, and students at this stage may not be familiar with Bessel functions and other advanced techniques. The mathematics can be simplified if a first-order reaction is studied instead of a second-order reaction.

A great many reactions follow first-order kinetics or pseudo first-order kinetics over certain ranges of experimental conditions.^[2] Examples are the gas-phase decomposition of sulfur chloride, the radioactive disintegration of unstable nuclei, the hydrolysis of methyl chloride, CH_3Cl , the isomerization of cyclopropane to propenes, and the decomposition of dimethyl ether. A representative liquid phase chemical reaction, which can easily be followed, is the reaction between acetic anhydride and water. This is a first-order reaction with rate constant of 0.16 min^{-1} at room temperature. Using this as a model, the following problem is suggested.



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

PROBLEM

Given the same setup as described above (Figure 1) and considering a first-order reaction under the same conditions, perform the following:

1. Develop mathematical models to describe the three stages mentioned above.
2. Solve the models both analytically and numerically.
3. Considering the differential equation and the final solution describing stage one, show how to circumvent the difficulty of defining the initial condition.

SOLUTION

Stage 1

During this stage, the reactor is filling up and the contents are still below the overflow level. This means that both the concentration and the volume are changing with time. A component mass balance gives

$$\text{rate of accumulation} = \text{rate of input} - \text{rate of consumption}$$

Therefore

$$\frac{d}{dt}(VC) = FC_0 - VkC \quad (1)$$

or

$$V \frac{dC}{dt} + C \frac{dV}{dt} = FC_0 - VkC \quad (2)$$

but $V = Ft$ (by total mass balance, assuming constant density and flow rate and noting that at $t = 0$, $V = 0$). Equation (2) becomes, after some manipulation

$$\frac{dC}{dt} + \left(\frac{1}{t} + k\right)C - \frac{C_0}{t} = 0 \quad (3)$$

Equation (3) is a linear first-order differential equation, which can be solved by the integrating factor method. The integrating factor in this case is $t \exp(kt)$, and the final solution is

$$C = \frac{C_0}{kt} [1 - \exp(-kt)] \quad (4)$$

Note here that application of the initial condition has to follow physical sense, *e.g.*, at $t = 0^+$, $C = C_0$. This difficulty will be obvious in the numerical solution.

Regarding the final solution, the exponential term can be written in a series form as $\exp(-kt) \approx 1 - kt$, and upon substituting this into Eq. (4), it is easily shown that as time approaches zero, $C = C_0$.

Another approach to model this stage is working with the number of moles, N , of reactant in the reactor at any time. A molal balance gives

$$\frac{dN}{dt} = -kN + FC_0 \quad (5)$$

The final solution (note that at $t=0$, $N=0$) is

$$N = \frac{FC_0}{k} [1 - \exp(-kt)] \quad (6)$$

Stage 2

In this stage the volume is constant, but the concentration is still changing with time because the process, although continuous, is not yet steady. A component material balance gives

$$\begin{array}{ccccccc} \text{rate of} & = & \text{rate of} & - & \text{rate of} & - & \text{rate of} \\ \text{accumulation} & & \text{input} & & \text{output} & & \text{consumption} \end{array}$$

or

$$V \frac{dC}{dT} = FC_0 - FC - kVC \quad (7)$$

and therefore

$$\frac{dC}{dT} = \frac{C_0}{\tau} - \frac{C}{\tau} - kC \quad (8)$$

where

$$T = t - \tau = \text{time in minutes}$$

$$\tau = V/F = \text{time constant}$$

Again, Eq. (8) is a linear first-order differential equation, which can be solved by the integrating factor method; the integrating factor in this case is $\exp\left(\frac{1}{\tau} + k\right)T$. The final solution is

$$C = \frac{C_0}{\tau A} \left[1 + \left(\frac{C_1 \tau}{C_0} A - 1 \right) \exp(-AT) \right] \quad (9)$$

where $A = (1/\tau) + k$, and C_1 is the concentration at the beginning of stage two (at $t = \tau$).

Stage 3

In this stage, steady state prevails. Modeling of this stage can be approached either by simplifying Eq. (9) as $T \rightarrow \infty$ or by a component mass balance. Both will give, after some manipulation

$$C_s = \frac{C_0}{1 + k\tau} \quad (10)$$

NUMERICAL SOLUTION

The initial value problems (Eqs. 3 and 8) can be solved by a suitable Runge-Kutta subroutine (*e.g.*, IVPK or DIVPK from IMSL). Note that the initial condition for stage two is that $C = C_1$ at $T = 0$ (or $t = \tau$), where C_1 is the concentration at the end of stage one. The application of the initial condition to Eq. (3), when solving it numerically, may cause some confusion. Here we have to give a specific value at zero time, but at zero time Eq. (3) is not defined mathematically. This should not cause any difficulty if we consider the ap-

proach to $t=0$ rather than at $t=0$ itself. Thus, by considering the definition of a derivative, the two terms in Eq. (3) with time in the denominator can be rewritten as time approaches zero as

$$\lim_{t \rightarrow 0} \frac{C - C_0}{t} = \left(\frac{dC}{dt} \right)_{t=0^+}$$

Thus, the limiting form of Eq. (3) as time approaches zero is

$$\left(\frac{dC}{dt} \right)_{t=0^+} = -\frac{1}{2} kC_0 \quad (11)$$

which can then be used to start the numerical solution.

DISCUSSION

Startup is one of the interesting points of the system shown in Figure 1. The way we start up the system will affect the derivation and behavior of the model. In our case, for example, the reactor is initially empty, and thus we have to care about the definition of the initial conditions. Thus, we say that at $t = 0$, $V = 0$, but as $t \rightarrow 0^+$, $C = C_0$. This is important when one has to deal with Eq. (4) and its differential form, Eq. (3), but not with Eq. (6) because initially the number of moles is zero. But we measure the concentration and not the moles, so if we express the number of moles in terms of concentration, we will arrive at the same difficulty as above. It will be an interesting point if one considers the startup with a known volume and concentration of the reactant. I strongly encourage the students to try this and note the difference.

The analytical and numerical profiles, which describe the dynamic and steady-state behavior of the CSTR, are shown in Figure 2 for $kV/F = 2.5$. The two profiles agree, confirming the correctness of the analytical solutions. In Figure 3, the effect of the parameter kV/F is shown. This parameter can be affected by a change in flow rate and/or a change in temperature since, usually, the volume of the reactor is constant. In our case, temperature is constant at 25 °C (where $k = 0.16 \text{ min}^{-1}$), the molar feed concentration = 10.5 M, and $V = 3.8 \text{ l}$; thus the change in kV/F is affected by the change in F only. As can be seen, the approach to steady state is faster for lower values of kV/F . Shown in the figure are the limits of the three stages for the case of $kV/F = 3.0$. This makes the comparison easier for the other two cases where the time constant can be calculated from the data given above.

The mathematics involved here is simpler than it would be with higher orders of reaction, and because of this students will enjoy the process of modeling and will, hopefully, gain the courage and

experience to tackle more complicated problems.

ACKNOWLEDGMENT

The author wishes to acknowledge helpful discussion and suggestions by the editors of the "Class and Home Problems" section and the reviewers of this article.

NOMENCLATURE

C	concentration of the reactant at any time in mols/liter
C_0	concentration of the reactant in feed, mols/liter
C_1	concentration at the end of stage one, mols/liter
F	total flow rate, liter/min
k	reaction rate constant, min^{-1}
N	number of moles of reactant at any time, moles
t	time, min
T	time for stage two, min
V	volume of the reacting system, liter
τ	time constant, min

REFERENCES

1. Abu-Khalaf, A.M., *Chem. Eng. Ed.*, **28**(1), 48 (1994)
2. Hill, G.C., *An Introduction to Chemical Engineering Kinetics and Reactor Design*, 1st ed., John Wiley, New York, NY (1977) □

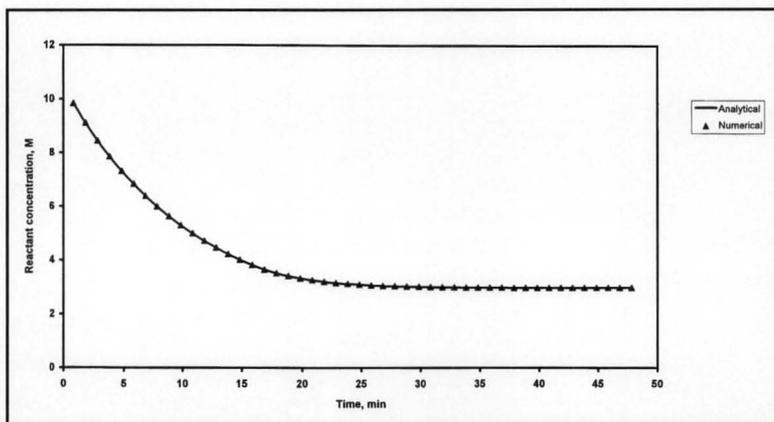


Figure 2. Analytical and numerical profiles.

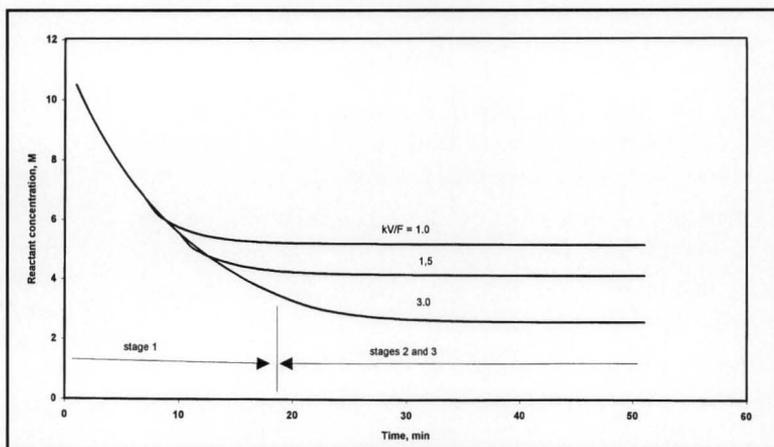


Figure 3. Analytical solution as compared to different values of kV/F .

ASEE

*1996 Annual Conference and Exposition
Sheraton Washington Hotel
Washington, DC
June 23-26, 1996*

————— Plan now to attend the Annual Conference! —————

Conference highlights include:

- ◆ **stimulating conference program** featuring more than 350 technical sessions
- ◆ only forum specifically designed for **all disciplines of engineering education**
- ◆ **bustling exposition** with the latest in products and services for the engineering educator
- ◆ **Awards Banquet**, featuring the renowned political satire group “The Capital Steps”
- ◆ special Wednesday “**Expo-Open House**” for engineering students
- ◆ ideal **networking** environment for educators, researchers, administrators and related industry professionals
- ◆ **self-contained** conference - all sessions, meal events and exposition in one place!
- ◆ close to the nation's most historic monuments and museums - - **great place to bring the family!**

ASEE PRISM will update you with ongoing conference details. Don't miss out on this exciting annual event!

For more information, feel free to contact ASEE Meetings and Conferences Department at (202) 331-3530.

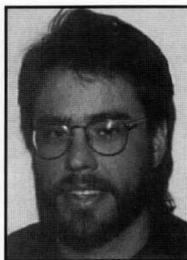
MATHEMATICA IN THE ChE CURRICULUM

JOHN R. DORGAN, J. THOMAS MCKINNON
Colorado School of Mines • Golden, CO 80401-1887

We have been active in incorporating Mathematica, a multifunctional general computer programming environment, into the chemical engineering senior year curriculum at the Colorado School of Mines (CSM). This integrated platform for symbolic, numeric, and graphical analyses has been used in the process control and reaction engineering courses. Students in these classes have had mixed but generally positive reactions toward its use. In this article we will describe our experiences and provide information that allows access to example problems posted on the Internet.

The use of Mathematica provides several advantages in teaching chemical engineering concepts—graphical accuracy in problem solutions presented in class, the ability to do more involved problems, and most importantly, discovery learning on the part of the student. Furthermore, the multimedia capabilities of Mathematica can be used to stimulate student interest in subjects that are inherently heavily mathematical in nature. Finally, we believe that the incorporation of this program into the curriculum provides a general engineering tool that can be useful to the students throughout their careers.

John R. Dorgan is Assistant Professor of chemical engineering and petroleum refining at Colorado School of Mines. He received his BS from the University of Massachusetts at Amherst and his PhD from the University of California at Berkeley. His research interests include phase transformations in liquid crystalline polymers, self-assembly of block copolymers at surfaces, polymer encapsulation of mixed wastes, and pedagogical methods in chemical engineering.



J. Thomas McKinnon is Assistant Professor of chemical engineering and petroleum refining at the Colorado School of Mines. He received his BS in chemical engineering from Cornell University in 1979 and his PhD from MIT in 1989. He teaches kinetics and thermodynamics at the undergraduate and graduate levels. His research interests are in combustion chemistry and applied industrial pyrolysis.

© Copyright ChE Division of ASEE 1996

COMPUTER INTEGRATION AT CSM

Our department's A. Bernard Coady Computing Laboratory is an excellent facility for such activities. It consists of 25 IBM RISC-6000 Model 220 computer workstations, a Model 350 file server, a Model 560 computational server, and a three-gun overhead projection system for the instructor's workstation. The ability to integrate powerful computer packages into classroom use rests on the availability of appropriate computer equipment, and we are truly fortunate to have such facilities readily available.

Our interest in incorporating Mathematica was sparked by Professor Stanley Sandler's essay, "Technological and Societal Change and Chemical Engineering Education."^[1] It pointed out that while computers have revolutionized the workplace, the biggest innovation in most college classrooms has been the introduction of the overhead projector. In the essay, Professor Stanley predicted the coming of a revolution in the delivery of education and educational methods due to changing technologies. We are in wholehearted agreement with this assessment.

It should be noted at this point that the hardware requirements for Mathematica are not severe. The program can be run on either an IBM compatible PC or on a Macintosh, provided that there is 8MB of RAM. We have used the program running on such machines coupled to a liquid crystal display device that sits atop an overhead projector. This allows quick in-class demonstrations, and the hardware necessary for this type of implementation is modest in cost. Such an arrangement works well and represents a viable alternative to dedicated computer classrooms.

MATHEMATICA AT CSM

CSM, like many other colleges, has a site license for Mathematica that allows an unlimited number of campus machines to run the program. All students at CSM are introduced to the capabilities of Mathematica in their freshman calculus sequence.^[2] Additionally, the program is used in our elementary stoichiometry class for finding roots of alge-

braic equations. This early integration into the curriculum provides an excellent background for use at the senior level.

Mathematica was introduced to the process control class in the spring of 1994 and into the reaction kinetics class the following semester. Thus, the program has been in classroom use for five consecutive semesters. During this time, several example programs have been developed that are of general interest to both the academician and the practicing engineer wishing to explore the use of the Mathematica platform.

WHAT IS MATHEMATICA?

Mathematica, in our opinion, is best described as a computational environment that allows symbolic manipulation, numerical analysis, and powerful graphical representation. Examples of the symbolic manipulation capabilities include differentiation and indefinite integration of functions, solving systems of linear algebraic or ordinary differential equations, and manipulation of Laplace transforms. Numerical capabilities include fitting data with polynomials or splines, root finding of algebraic equations, and solution of systems of nonlinear ordinary differential equations through numerical integration. Graphical capabilities include 2-D and 3-D representation and contour and parametric plots, as well as animation of a series of sequential graphs.

The syntax of Mathematica is logical, but can be cumbersome; we have found this to be the biggest stumbling block for students in our classes. For example, the following command analytically solves a linear differential equation:

$$\text{DSolve}\left[\{T' [t] - a T[t] + b = 0, T[0] = 0\}, T[t], t\right]$$

This command, translated, says to solve the differential equation

$$\left[\frac{dT}{dt}\right] - aT + b = 0$$

subject to the following initial condition:

$$T(t = 0) = 0$$

Mathematica returns with the analytical solution in the form

$$\left\{\left\{T[t] \rightarrow b/a - (b * E^{(a * t)})/a\right\}\right\}$$

The mixed use of parenthesis, square brackets, and curled brackets can be confusing for engineers used to programming in FORTRAN.

Fortunately, the built-in Help Menu found in Mathematica can be used to great advantage in overcoming syntactical errors. This is due to the fact that within the Help Menu a "Function Browser" can be invoked. Searching through this Browser by subject allows the user to find the command of interest along with a short description of its function. In addition, the syntax of the command is given and may be pasted directly into the program being written. This obviates

Spring 1996

... Mathematica provides several advantages in teaching chemical engineering concepts—graphical accuracy in problem solutions presented in class, the ability to do more involved problems, and most importantly, discovery learning on the part of the student.

the need for directly typing in command syntax.

The resources associated with developing Mathematica applications are considerable and can be used to great advantage when incorporating the program into the chemical engineering curriculum. Most significant is the existence of MathSource, an electronic bulletin board for public domain programs and example problems. The bulletin board can be accessed through the Mathematica home page using any web browser. The URL for MathSource is

<http://www.wri.com.mathsource>

All of the usual web searching capabilities are supported at this location.

In addition, the bulletin board may be accessed by e-mail at mathsource@wri.com. Searches for topics of interest can be performed by simply sending the e-mail message "Find *subject*" where *subject* is the field of interest (chemical engineering, perhaps). For general help in using MathSource, send the above one-line message with *intro* as the subject. In addition to the applications bulletin board, the program is supported by a very competent technical staff that can be contacted regarding questions and possible bugs at the e-mail address support@wri.com.

MATHEMATICA IN PROCESS CONTROL

Our use of Mathematica in the process control class centers on the subjects introduced in the early part of the semester. Roughly the first one-third of the course deals only with process dynamics; formulation of state models and calculation of uncontrolled response to input changes are addressed during this time period. Experience shows that the program can be used to great advantage in demonstrating the difference between nonlinear process models and the corresponding linear models that form the basis of modern control theory.

A relevant example of this type of use can be taken from a homework assignment during the spring 1995 semester in which the students were asked to compare the behavior of draining liquid tanks of varying geometry (cylindrical, conical, and spherical) for the case in which the outflow is proportional to the square root of the liquid level. The process model for the cylindrical tank appears in most textbooks, the conical tank model is developed in lecture, and the spherical tank model is assigned as an earlier, independent homework assignment. A simple representation of the tank geometries and the resulting process models is given in

Figure 1 (next page). In these models, F_i is the volumetric inlet flow, F_o is the outlet flow, β represents the discharge coefficient, h is the liquid level height in the tank, and h_s is the initial steady-state level.

The objective of the Mathematica assignment is to compare the full nonlinear process behavior to the linearized approximation and to draw conclusions about the severity of the linearization approximations.

For this particular problem, an example solution for the cylindrical tank is provided as part of the problem statement. The heart of the assignment consists of using only three Mathematica commands: DSolve[] for solving the linearized equations, NDSolve[] for numerically solving the nonlinear equations, and Plot[] for comparing the solutions. Figure 2 is part of an actual program listing for a solution submitted by one of the students.

From this straightforward application, students learn that linear approximations may either under- or overestimate the actual system response (in this case, the time required to empty the given tank). In addition, they experience the phenomena that some systems deviate more quickly from their linear approximations than do others and that this depends on the strength of the nonlinearities present in the process. The type of discovery learning which the program allows is thought to be advantageous toward student learning and content retention.^[3]

Another example from the process control class involved the use of the symbolic capabilities for manipulation of Laplace transforms. The assignment in this case was to write a general purpose simulator for the response of any linear second-order system and to test the response of the system toward different types of forcing functions. This assignment was given in the fall 1994 and spring 1995 semesters.

As a preface to this assignment, the students are given an example program that constitutes a general purpose simulator for a first-order system. Recall that the standard form for a linear first-order system is

$$\tau_p \left(\frac{dy}{dt} \right) + y = K_p f(t)$$

where τ_p is the process time constant, K_p is the static gain, and $f(t)$ is the forcing function. The resulting transfer function is

$$G(s) = \frac{K_p}{\tau_p s + 1}$$

where s represents the independent variable in Laplace space.

The demonstration program allows the user to input his or her own function for $f(t)$. This user-defined forcing function

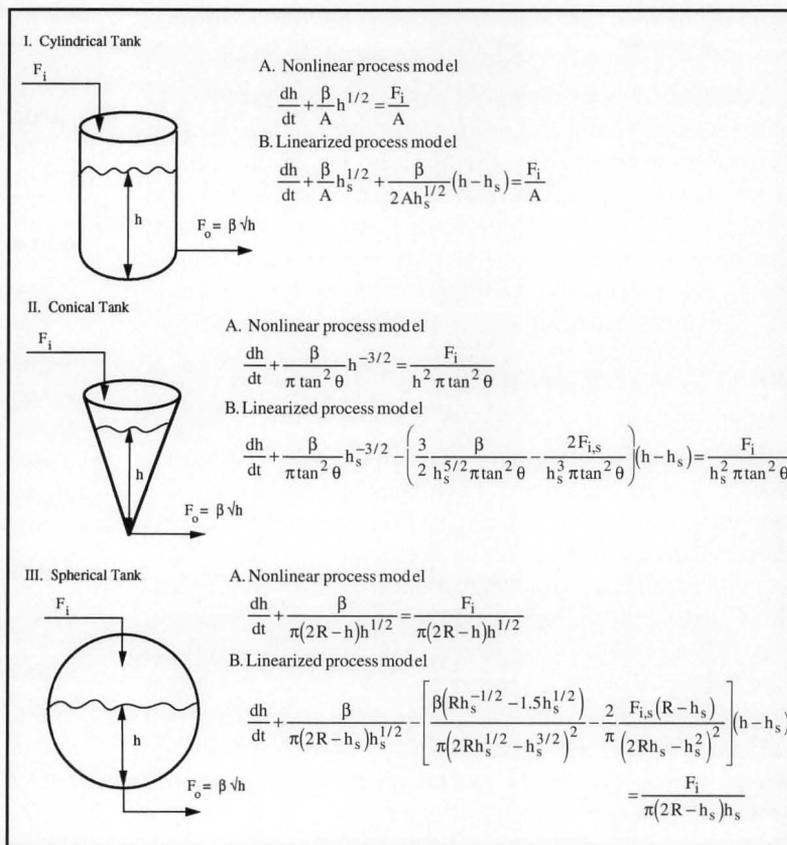


Figure 1

is then transformed, multiplied by the transfer function, and inverted to give the time domain response of the system to the given forcing function (which is defined as a plot versus time). The students are asked to run this program for a variety of different forcing functions: step inputs, ramps, and sine waves. In addition, the students run the program for different values of the system parameters K_p and τ_p , thus experiencing the meaning of these quantities directly. This type of exploration learning can be highly effective.

Based on the example given, the students are asked to rewrite the program to be applicable for second-order systems. The standard form of the transfer function in this case is

$$G_2(s) = \frac{K_p}{\tau^2 s^2 + 2\tau\zeta s + 1}$$

where ζ is the damping coefficient, while τ_p and K_p and $f(t)$ have the same meanings as above. For second-order systems, when the damping coefficient is less than unity, oscillatory behavior is observed.

While the students' solutions generally mimic the example program, we wish to emphasize that we are not trying to teach Mathematica programming, per se, but rather are using the capabilities of the program in order to demonstrate concepts in chemical engineering. Again, the students are asked to test their simulator with a variety of forcing func-

```
(* PART 2 - THE CONICAL TANK*)
Clear [Fi, A, hs, beta, theta, Fis]

(* Define a function which is the linear O.D.E.*)
conf[t_] := conh'[t] - Fis hs^-2 + beta/(N[Pi] N[(Tan [theta])^2]) hs^(-3/2)
           -hs^-2 (Fi-Fis)-(3 beta/(2 N[Pi] N[(Tan [theta])^2]) hs^(-5/2) -
           2 Fis hs^-3) (conh[t]-hs)

(* Solve the linear O.D.E with the initial tank height. *)
sol3 = DSolve[{conf[t]==0, conh[0]==hs},conh[t],t];

(* Define a function which can be plotted. *)
conhsolve[t_] := conh[t] /. sol3[[1]]

(* Define a function which is the non-linear O.D.E. *)
connlh[t_] := connlh'[t] + beta/(N[Pi] N[(Tan [theta])^2]) connlh[t]^(-3/2) -
           Fi connlh[t]^(-2)

(* Numerical solution requires parameter values. *)
Fi = 0;
Fis = 0;
beta = 1;
hs = 5;
theta = N[Pi]/6;

(* Solve the non-linear O.D.E. with the initial tank height set to hs m. *)
sol4 = NDSolve [{connlh[t]==0,connlh[0]==hs},connlh[t],{t,0,23}];

(* Convert the numerical solution to a function which may be plotted. *)
connlhsolve[t_] := connlh[t] /. sol4

(* Plot the two functions for comparative purposes. *)
Plot[{conhsolve[t],connlhsolve[t]},{t,0,23}];
```

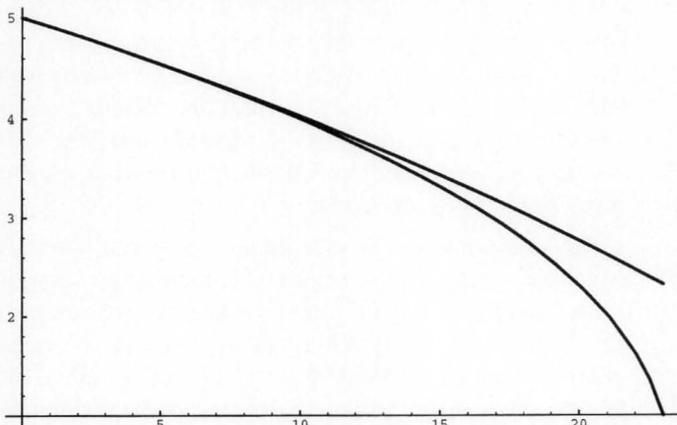


Figure 2

tions for different parameter values. The responses of a second-order system to a unit step input for both overdamped ($\zeta > 1$) and underdamped ($\zeta < 1$) cases are explored.

The ability of students to explore system dynamics using these approaches is important in making the connection between process models and real-world behavior. Later in the semester, the excellent process simulation capabilities of PICLES are used as part of the class.^[4] Thorough preparation in the fundamentals means the students are better prepared for logically connecting the mathematics of process modeling with observable system dynamics.

MATHEMATICA IN REACTION KINETICS

We introduced Mathematica in our senior-level kinetics and reactor design class in the fall 1994 semester. Solving differential equations that result from the reactor design equations is a large part of this class, along with root finding and plotting of results. In previous semesters, we used Polymath for these tasks.^[5] This program has the advantage of being very easy to use; we found that the students needed

little more than a ten- or fifteen-minute introduction to the program in lecture to use it effectively.

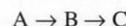
But we found that the ODE solving routines in Polymath are not as robust as those in Mathematica, particularly with regard to the stiff differential equations that routinely arise in chemical kinetics problems. Furthermore, the programming environment allows more complex problems to be constructed; the results of one calculation (e.g., a numerical integration) can be fed directly into the subsequent one (e.g., finding a root). The price to pay for this increased usefulness is, of course, a much steeper learning curve.

We describe below some of the homework problems for which Mathematica was used. It should also be noted that our textbook, *Elements of Chemical Reaction Engineering*^[6] also lists a few Mathematica examples.

1. Chemical equilibrium • The first week of our class is a review of chemical reaction equilibrium. The FindRoot[] function in Mathematica is used to evaluate the roots of high-order polynomials to solve for equilibrium conversion. The programming environment in Mathematica allows us to easily explore the effect of temperature changes on equilibrium composition. One difficulty for new users is in discovering which, apparently equivalent, Mathematica function is appropriate for a given problem. In the case of reaction equilibrium, both NSolve[] and FindRoot[] should work, as described by Wolfram.^[7] The former function finds all the roots to a polynomial, while the later finds a root to any function over a specified interval. It is only by trial and error that the user discovers that NSolve[] rarely works for these

problems and that FindRoot[] is the more useful approach. This highlights the importance of the instructor directing the students in lecture before they start out on a problem.

2. Comparison of ODE solution methods • Since solving ordinary differential equations (ODEs) is such a large part of the class, we spend one entire homework assignment exploring different solution methods. We start with a relatively simple first-order batch reactor problem with the reaction steps



The solution for [B] as function of time can be found analytically by hand using the integrating factor method. Next, we move on to a more complicated reaction network with parallel reactions and reversibility:

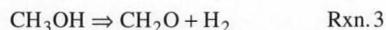
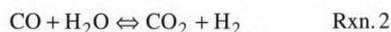
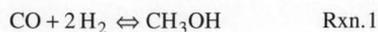


This system of ODEs has an analytical solution, but it would be rather difficult to solve by hand (and solving difficult ODEs is not the objective of our course). For this job, we turn to the NSolve[] function in Mathematica. The raw output of NSolve[] for this

system is exceedingly cumbersome, but with the use of the Simplify[] function, it becomes at least somewhat manageable.

We then use this same reaction network to explore numerical solutions to ODEs. The existence of the analytical solution allows the students to examine the errors that can arise in numerics. They first do a solution by implementing Euler integration using a spreadsheet. In the lecture discussion of Euler integration, we also show how Runge-Kutta methods improve the Euler integration results. The integration stepsize can be varied and the resulting time profiles are compared to the analytical solution. Finally, we solve the same system numerically, using the NDSolve[] function. Here there is no discernible difference between the analytical and the numerical result.

● **3. Multiple reaction with phase change** • Our most ambitious Mathematica homework problem was to explore the effect of temperature on a system that includes both multiple reactions (both series and parallel) and phase change. We postulated that a new methanol synthesis catalyst had been discovered that has reasonable activity around 400K and 50atm. The reaction considered are



Arrhenius parameters are provided for all the reactions. The students find the reverse rates of Rxns. 1 and 2 from the reaction thermodynamics. The feed is specified to be a mixture of CO, CO₂, H₂, steam, and inert (N₂). The volume of the reactor and the total molar feed rate are specified. The vapor pressure of methanol is computed from the Harlacher equation. Although the deviations from ideality are high at these conditions, we still use the ideal gas law for the purpose of simplification. The objective is to find the temperature at which the methanol production rate is maximized. Increasing the temperature obviously favors faster kinetics, but this advantage is rapidly diminished by the approach to equilibrium of Rxn. 1 and the more rapid product decomposition by Rxn. 3. Furthermore, the condensation of methanol at low temperatures pulls the equilibrium conversion of Rxn. 1 to the right.

A multistep solution process is required for this problem and can be performed in the Mathematica environment. First, the students must numerically solve the six coupled ODEs (one for each species) for the gas-phase problem over the whole reactor volume. Next, the volume V_{crit} , at which methanol first begins to condense, must be identified from the methanol mole fraction and the solution to the Harlacher equation. After condensation ($V > V_{\text{crit}}$), the relationships between moles and mole fractions are different, and a second numerical integration must be carried out from V_{crit} to V_{final} . The process is repeated at different temperatures until the optimum temperature is identified.

● **4. Unsteady flow problems** • Unsteady flow problems are ideal as examples where all the terms of the mole balances must be considered. One of our favorite problems of this nature is the unsteady-state startup of three CSTRs in series (found in Fogler,^[6] Problem 4-32). The students write three coupled time-dependent ODEs for the conversions in each stirred tank reactor and solve them using NDSolve[]. Figure 3 gives a listing of the Mathematica

commands needed for this problem.

IMPLEMENTATION PROBLEMS

While we are in general very pleased with Mathematica and plan to continue using it, we would be remiss in an article of this nature if we failed to point out some of the difficulties we encountered. Probably the greatest source of frustration on the part of the students is the inscrutable error messages that are spawned by Mathematica. The incorrect definition of a variable within NDSolve[] generates many lines of error messages giving no real hint of the problem, while at the same time (and more troublesome) holding out several red herrings leading to misplaced debugging efforts. The second greatest source of frustration is that Mathematica holds values of variables until they are explicitly cleared. One solution to this problem is to include the function Clear[] at the beginning of every Mathematica problem where every variable used is included in the square brackets. When a change is made to the notebook, the problem is rerun from the top (menu commands: Action, Evaluate, Evaluate Notebook). This action removes all previous values from the variables and resets them to the desired value. The value of carrying out this step, although somewhat cumbersome, cannot be stressed enough.

The solution to the first problem is more difficult. We generally assign it to a lack of practice using debugging skills brought on by the increased use of software packages by our students. Although all students do take a programming class (FORTRAN is taught at CSM), they practice very little in subsequent classes. In many ways, Mathematica can be considered to be a programming language, thus the same debugging strategies can be used. We find that it is necessary to include a discussion of debugging methods in lectures when discussing problem solutions using Mathematica.

CONCLUSIONS

Mathematica is a very powerful computational tool that can be used successfully in the undergraduate chemical engineering curriculum. We have used the program for several semesters and in different classes at the senior level. Based on our experiences and recent trends in the development of new media for the delivery of education, we expect the use of programs that can combine symbolic, numeric, and graphical capabilities to increase.

In the process control class, Mathematica has been implemented in order to elucidate the difference between nonlinear system response and the linearized approximation of this behavior. Additionally, the symbolic manipulation capabilities associated with the Laplace transform have been exploited in order to allow discovery learning on the part of the students.

The use of Mathematica in the reaction engineering class has greatly expanded our horizons regarding the types of problems we can address. The robust ODE solver in Mathematica frees us from the constraint of artificially selecting reaction parameters. The programming environment within Mathematica allows results of one calculation to be automatically cascaded into the next. Furthermore, these assignments are somewhat open ended, and there are few

software limits placed on the more ambitious students who want to develop elegant solutions. Finally, the advanced plotting capabilities of the program allow visualization of the results for different cases.

Beyond the benefits of enhanced education in chemical engineering, we believe that the type of computer environment that Mathematica represents is here to stay. As a result, the exposure that students receive when using the program introduces them to a computational tool that should prove valuable to them in the future regardless of the specifics of their career paths.

REFERENCES

1. Sandler, S.I., "Technological and Societal Change and Chemical Engineering Education," Phillips Petroleum Company Lecture (1993)
2. Hagin, F.G., and J.K. Cohen, *Calculus Explorations with Mathematica*, Prentice-Hall, Englewood Cliffs, NJ (1995)
3. Wankat, P.C., and F.S. Oreovicz, *Teaching Engineering*, McGraw-Hill, New York, NY (1993)
4. Cooper, D.J., "PICLES," *Chem. Eng. Ed.*, **27**(4), 176 (1993) and Cooper, D.G., "PICLES: The Process Identification and Control Laboratory Experiment Simulator," *CACHE News*, 6-12 (1993)
5. Polymath, developed by M. Cutlip and M. Sacham. Available from CACHE Corporation, PO Box 7939, Austin, TX 78713
6. Fogler, H.S., *Elements of Chemical Reaction Engineering*, 2nd ed., Prentice Hall (1992)
7. Wolfram, S., *Mathematica: A System for Doing Mathematics by Computer*, 2nd ed, Addison Wesley (1991)

APPENDIX

Obtaining Examples Through e-mail

As stated in the body of this article, the MathSource bulletin board may be accessed through the Internet at the e-mail address mathsource@wri.com

To access the process control examples described in this article as well as other control examples, send the e-mail message

Find Control

The MathSource server will send a listing of all examples containing these keywords. In the returned file, each of the listings will have an identifying number (as of this writing, the specific numbers for our own examples are not known).

One process control application that is already available is called *control.m*. This public domain package allows students to easily generate Bode and Nyquist diagrams, root locus plots, and most other types of plots used in a control course.

To obtain copies of the examples of interest, simply send MathSource another e-mail message asking it to send the appropriate identifier. As an example, if the message

Send 0202-554-0011

is sent to the MathSource address, an ASCII text file of the MathSource Technical Report will be returned to the requester through e-mail. Further details of the downloading procedure may be found in this document. □

```
(* CR418 HW 7.1 Fogler Problem 4-32 *)
(* Unsteady Flow Problem - Startup of 3 Series CSTRs *)
(* Rxn: A + B --> C, elementary. Equimolar feed rate *)
(* Find the time required for the exit of the third *)
(* reactor to reach 99% of its steady-state value *)

(* Important! Start every problem by clearing *)
(* previous values *)
Clear[dnaldt, dna2dt, dna3dt, fao, vdot, ca1, ca2, ca3,
na1, na2, na3, nalr, na2r, na3r, v, fao, vdot,
tfinal, k]

(* Mole balances for species A in each reactor. *)
(* Writing these equations in the form: *)
(* "accum. = in - out + generation" aids debugging *)
dnaldt = fao - vdot ca1 - k ca1^2 v;
dna2dt = vdot ca1 - vdot ca2 - k ca2^2 v;
dna3dt = vdot ca2 - vdot ca3 - k ca3^2 v;

(* Auxiliary equations. Relate all the variables in *)
(* problem to the dependent variables of the ODEs, and *)
(* assign values to the constants. "ca3ss" is the *)
(* steady-state value solved in a separate notebook. *)
ca1 = nal[t]/v; ca2 = na2[t]/v; ca3 = na3[t]/v;
fao = 20; v = 200; vdot = 20; tfinal = 65; k = 0.025;
ca3ss = 0.609;

(* NDSolve numerically evaluates the coupled ODEs *)
(* given the initial conditions. *)
sol = NDSolve[{na1'[t] == dnaldt,
na2'[t] == dna2dt,
na3'[t] == dna3dt,
na1[0] == 0,
na2[0] == 0,
na3[0] == 0},
{na1, na2, na3},
{t, 0, tfinal}];

(* The direct output of NDSolve is a List. The *)
(* Replace operator (/.) extracts the desired function *)
(* from the List. *)
nalr = na1 /. sol[[1]]; na2r = na2 /. sol[[1]];
na3r = na3 /. sol[[1]];

Plot[{nalr[t]/v, na2r[t]/v, na3r[t]/v}, {t, 0, tfinal},
GridLines -> Automatic, Frame -> True,
FrameLabel -> {"Time (min)", "Conc. (mol/L)"}];

(* Find the point at which the exit conc. of Reactor 3 is *)
(* 99% of its steady-state value. *)
FindRoot[na3r[t]/v == 0.99 ca3ss, {t, 0}]
{t -> 59.6826}
```

Figure 3.

LOW-COST EXPERIMENTS IN MASS TRANSFER

Part 2¹

I. NIRDOSH, M.H.I. BAIRD²

Lakehead University • Thunder Bay, Ontario, Canada P7B 5E1

Liquid-liquid (or solvent) extraction is an important unit operation in mineral processing, in nuclear and non-nuclear waste treatment, and in the chemical and pharmaceutical industries. It usually involves the transfer of a solute from an aqueous to an organic phase, or vice versa. The two phases are generally immiscible with each other, and one phase is *dispersed* in the other, which is known as the *continuous* phase. This provides a large interfacial area for mass transfer and improves the process kinetics.

Prediction of mass transfer coefficients for a solvent extraction process becomes difficult because of the absence of any accurate knowledge of the interfacial area and is complicated further by the influence of ionic strength and surface contaminants on the area.

The study of extraction rates at the bench scale, with a known interfacial area, has been carried out using batch cells

Inder Nirdosh received his BSc and MSc in chemical engineering from Panjab University (India) and his PhD from Birmingham University (United Kingdom). He joined Lakehead University in 1986, and his research interests are in the fields of mineral processing and electrochemical engineering.



Malcolm Baird received his PhD in chemical engineering from Cambridge University in 1960. After some industrial experience and a post-doctoral fellowship at the University of Edinburgh, he joined the McMaster University faculty in 1967. His research interests are liquid-liquid extraction, oscillatory fluid flows, and hydrodynamic modeling of metallurgical processes.

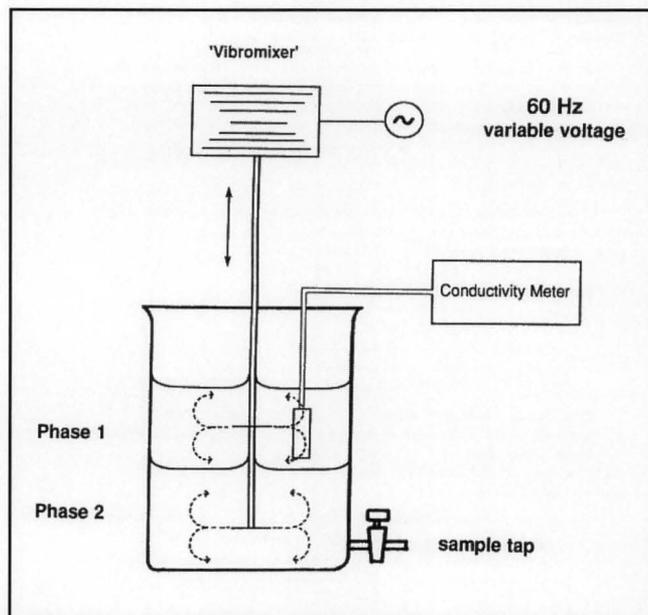


Figure 1. The apparatus.

with rotary agitation. Special baffles are provided to ensure that the liquid-liquid interface remains flat. The original Lewis cell^[1] was modified by Bulicka and Prochazka,^[2] who incorporated vertical baffles and a cylindrical perforated grid in the design in order to achieve greater turbulence together with increased stability of the interface. A brief review of various stirred cells is given by Lo, *et al.*^[3]

The objective of this experiment is to introduce chemical engineering students to a simple technique of predicting mass transfer coefficients using equipment with a well-defined interfacial area.

¹Part 1 appeared in the last issue of CEE, Vol. 30, No. 1 (1996)

²Address: ChE Department, McMaster University, Hamilton, Ontario, Canada L8S 4L7

THEORY

Solvent extraction of acetic acid from an organic phase into an aqueous phase is taken as an example because it is a non-reacting system. The concentration increase of acetic acid in water is followed with time. The rate of acetic acid transfer is assumed to be first order with respect to the difference between the final ($C_{a\infty}$) and the actual (C_a) solute concentration. For a volume V_a of the aqueous phase, the rate of change of solute concentration (dC_a/dt) can be expressed by

$$V_a \frac{dC_a}{dt} = k_a A (C_{a\infty} - C_a) \quad (1)$$

which can be integrated as

$$\int_{C_{a_i}}^{C_a} \frac{dC_a}{(C_{a\infty} - C_a)} = \frac{k_a A}{V_a} \int_0^t dt \quad (2)$$

yielding

$$\ln(C_{a\infty} - C_a) = \ln(C_{a\infty} - C_{a_i}) - \frac{k_a A}{V_a} t \quad (3)$$

where

C_{a_i} initial concentration of acetic acid in water (generally zero)

C_a acid concentration in water at time t

k_a local aqueous phase mass transfer coefficient

A interfacial area that is kept constant during the experiment

$C_{a\infty}$ aqueous phase acetic acid concentration at equilibrium

Equation (3) indicates that by plotting $\ln(C_{a\infty} - C_a)$ versus t , a linear line of negative slope ($-k_a A / V_a$) is obtained, from

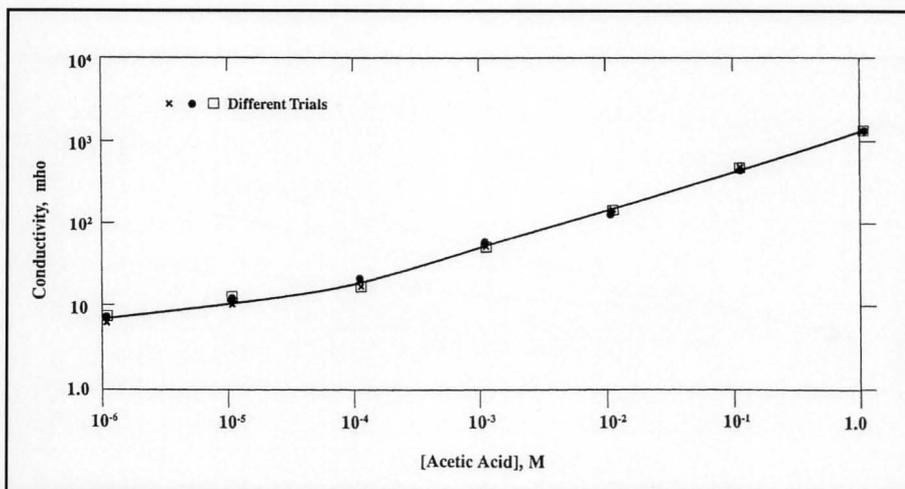


Figure 2. A typical calibration curve.

The objective of this experiment is to introduce chemical engineering students to a simple technique of predicting mass transfer coefficients using equipment with a well-defined interfacial area.

which k_a can be calculated.

APPARATUS

A sketch of the apparatus is shown in Figure 1. It is a modification of the Lewis cell.^[4] A 1-liter glass beaker is used as the extraction cell. The cell has a sample draw-off tap at the bottom that is installed by glass blowing. Agitation is achieved by a single-phase Chemapec Inc. Vibro Mixer Model EI-11043 operating at standard 60-Hz frequency and powered through a Variac to change the amplitude of vibration (degree of agitation). Mixing is provided by two 4.6-cm diameter stainless steel agitator discs mounted on the shaft of the Vibro Mixer. The liquid streams outward from the edges of the vibrating discs and circulates as shown in the figure. Mixing within the phases can also be achieved by a small impeller agitator provided the interface stays flat.

EXPERIMENTAL PROCEDURE

The organic phase may be either lighter (such as kerosene as Phase 1) or denser (such as carbon tetrachloride as Phase 2) than water. The concentration of acetic acid in the aqueous phase at any time may be determined by either titrating a small sample of solution or by monitoring the conductivity of the aqueous phase, which would eliminate the need for removal of aqueous samples for titration. Sample removal has some effect on the value of V_a , which is assumed to

remain constant during the integration of Eq. (2). Although the present data have been obtained with carbon tetrachloride, the use of a relatively non-toxic organic phase denser than water (such as methylene chloride, CH_2Cl_2) is recommended. When using a lighter organic phase, the conductivity probe should be submerged in the aqueous phase before adding the organic phase in the cell.

On the other hand, when a denser organic phase is used, it should be added to the cell first, then the water, and then the conductivity probe should be placed in the top aqueous layer. A calibration curve can be drawn for $[\text{CH}_3\text{COOH}]$ versus con-

ductivity to facilitate analysis of results. A typical calibration curve is plotted in Figure 2 that indicates excellent reproducibility and linearity in the $[H^+]$ range of 10^{-4} to 1 M. The data plotted in Figure 3 indicate that the results obtained with titrations versus conductivity measurements are within $\pm 5\%$ of each other.

Based on the experimental investigations followed for this study, the following procedure is recommended for the setup using CCl_4 and conductivity measurements:

1. Take 3 L of CCl_4 and add about 26 mL of glacial acetic acid. Mix well and use it as a stock solution. Titrate a 10-mL sample to determine the exact acid concentration. Adding 10 mL of water before titration is recommended.
2. Take 450-500 mL of the stock solution in the extraction cell.
3. Adjust the Vibro Mixer so that the agitator discs would be in the middle of each phase.
4. Take the same volume (450-500 mL) of water and add it quickly to the cell, pouring it over the top disc rather than directly into the organic phase. This will keep the transfer of acetic acid during start-up to a minimum.
5. Place the conductivity probe in the aqueous phase and start the agitator at a fixed voltage setting on the Variac (fixed amplitude).
6. Start conductivity measurements immediately, initially using one-minute intervals and later at longer intervals. Discontinue measurements when conductivity changes are insignificant over a ten-minute period.
7. Mix the two phases vigorously, preferably in a separatory funnel, to establish equilibrium. Measure the conductivity of the aqueous phase at equilibrium to determine $C_{a\infty}$.
8. Using the predrawn calibration

curve (Figure 2), obtain the concentration values corresponding to the recorded conductivity values.

9. Take a sample of each phase and titrate to determine the acid content. Use these values to verify the mass balance and the concentration values obtained from the calibration curve.
10. Repeat twice more, each time with a fresh batch of CCl_4 stock solution, but a different Variac setting.
11. Plot $-\ln(C_{a\infty} - C_a)$ versus t for each of the three cases and determine k_a values from the slopes.

TYPICAL RESULTS AND DISCUSSION

Figure 4 is a plot of $-\ln(C_{a\infty} - C_a)$ versus t for three different agitation rates. The plots are linear, conforming to Eq. (3), and indicate that the slope (and hence the mass transfer coefficient) in each case increases with the increase in rate of

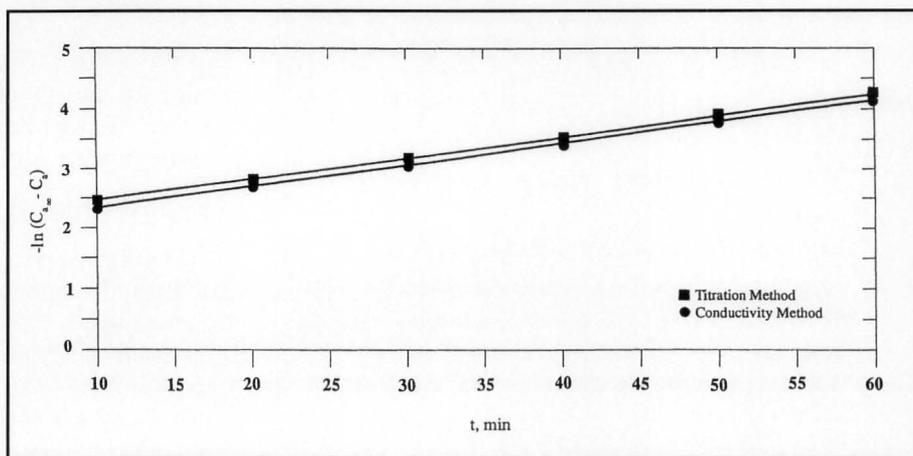


Figure 3. Comparison of conductivity versus titration measurements for obtaining acid concentrations.

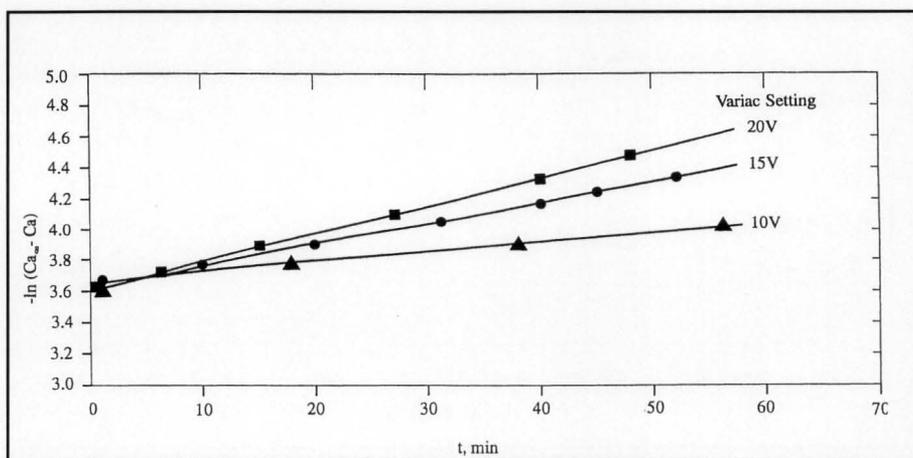


Figure 4. Typical $-\ln(C_{a\infty} - C_a)$ vs. t plots.

agitation. This is also depicted by the data (k_a versus Variac setting) plotted in Figure 5.

Figure 6 is a plot of k_a versus the aqueous phase viscosity. The changes in the phase viscosity were achieved by dissolving varying amounts of sucrose in water. The plot clearly indicates the adverse effect an increase in the viscosity has on the mass transfer coefficient.

CONCLUSIONS

- ▶ The class should be divided into various groups.
- ▶ Each group should follow steps 1 through 11 above.
- ▶ Various groups should use aqueous or organic phases of varying viscosities (the organic phase viscosity may be changed by adding various amounts of heavy

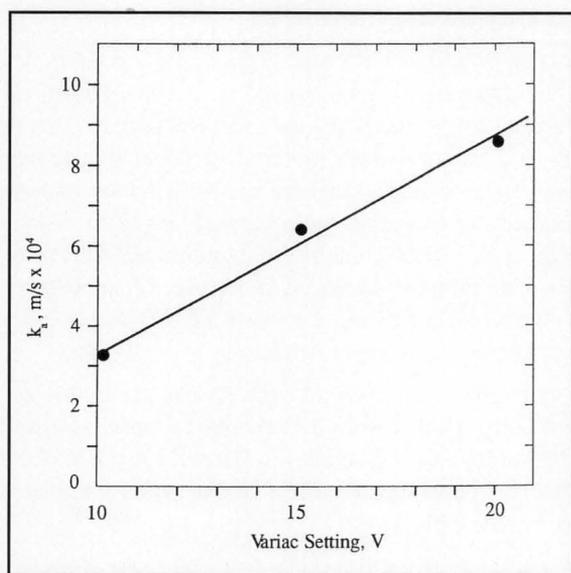


Figure 5. Dependence of k_a on degree of agitation.

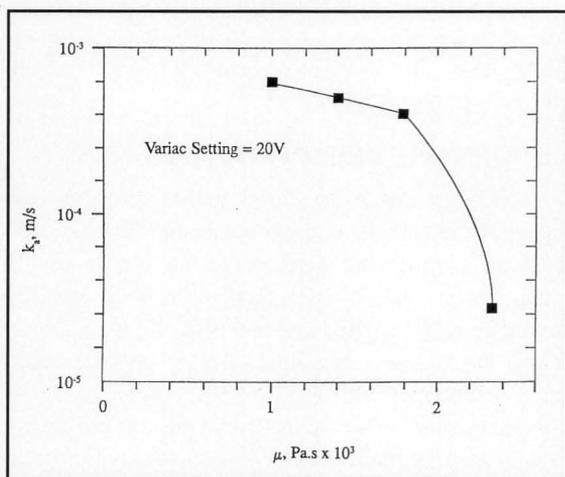


Figure 6. Dependence of k_a on viscosity of aqueous phase.

mineral oil to the organic phase) and submit a formal report containing discussion on:

- Comparison of $\ln(C_{a_{\infty}} - C_a)$ versus t curves for various Variac settings
- Dependence of k_a on liquid viscosity

POSSIBLE FUTURE PROJECTS

In future years the experiments may include investigation of a) the dependence of k_a on temperature, and b) the analysis based on the changes in acid concentration in the organic phase rather than the aqueous phase, *e.g.*, from the following equations:

$$V_o \frac{dC_o}{dt} = k_o A (C_o - C_{o_{\infty}}) \quad (4)$$

NOMENCLATURE

- A interfacial area (cross-sectional area of the beaker)
- C bulk phase concentration of acetic acid at any time
- k local mass transfer coefficient
- t time
- V phase volume

Subscripts

- a aqueous phase
- i initial
- o organic phase
- ∞ equilibrium, final

ACKNOWLEDGMENTS

Financial support for this work was provided by the Natural Sciences and Engineering Research Council of Canada. Thanks are due to Mr. J.S. Chatha for obtaining some of the experimental data.

REFERENCES

1. Lewis, J.B., "The Mechanism of Mass Transfer of Solutes Across Liquid-Liquid Interfaces. I. The Determination of Individual Transfer Coefficients for Binary Systems," *Chem. Eng. Sci.*, **3**, 248 (1954)
2. Bulicka, J., and J. Prochazka, "Mass Transfer Between Two Turbulent Liquid Phases," *Chem. Eng. Sci.*, **31**, 137 (1976)
3. Lo, T.C., M.H.I. Baird, and C. Hanson, *Handbook of Solvent Extraction*, John Wiley, New York, NY, pp. 113-115 (1983)
4. Nirdosh, I., and M.H.I. Baird, "Copper Extraction in a Vibrating Plate Cell," *AIChE Symp. Ser.*, No. 173, Vol. **74**, 107 (1978) □

ERRATUM

In the book review, *Chemical Thermodynamics: Basic Theory and Methods*, 5th ed., by Irving M. Lkutz and Robert M. Rosenberg, reviewed by Pablo G. Debenedetti in *Chemical Engineering Education*, **30**(1), 69 (1996), the sixth sentence of the fifth paragraph should read

Similarly, the definition of an ideal gas as one satisfying $PV = RT$ and, in addition, having a volume-independent energy is redundant.

CURRENT TRENDS IN CHEMICAL REACTION ENGINEERING EDUCATION

MAZEN SHALABI, MUHAMMAD AL-SALEH, JORGE BELTRAMINI, DULAIHAN AL-HARBI
King Fahd University of Petroleum and Minerals • Dhahran 31261, Saudi Arabia

Chemical engineering is a practical specialization combining several fundamental scientific disciplines within the field of engineering in order to solve the problems and challenges facing mankind. It evolved around the beginning of this century in response to the world's increasing industrialization. Required courses for chemical engineering majors almost universally include a sequence of multidisciplinary courses. Chemical reaction engineering (CRE), the study of the basic knowledge of chemical kinetics and reactor design, is the most important area of study and is the main area that distinctly characterizes chemical engineering from other engineering disciplines.

CRE also uses areas (such as thermodynamics, transport phenomena, and other related disciplines) in analyzing small- and large-scale reaction systems. In a recent article, Doraiswamy^[1] addressed the fact that students majoring in CRE not only must have a proper background in the fundamentals (such as ideal reactor design), but they should also tackle new and challenging areas, such as biochemical, micro-electronic, polymer, and electrochemical reaction engineering. He also stressed the importance of CRE education as a possible "interdisciplinary single umbrella" to cover all these different disciplines. If one basic course is not enough, Savage and Blaine^[2] have proposed that additional elective courses should

be introduced to cover these areas.

Another important CRE area is catalysis, especially heterogeneous catalysis—it has evolved as a consequence of the widespread use of the many catalytic reaction systems in industry and is not usually covered in depth in engineering courses. Heterogeneous catalysis courses and their importance in engineering education have been reviewed by Vannice^[3] and Miranda.^[4] They combined the traditional material of catalysis with the more advanced knowledge of solid state, surface chemistry, and material processing, such as sol-gel technology and chemical vapor deposition.

A more thorough review of CRE education can be found in an article by Dudukovic^[5] comparing the results of a 1982 AIChE survey of CRE courses in US and Canadian chemical engineering departments with a similar study completed by Eisen^[6] in the early 1970s.

This article reports the results obtained from a similar survey, conducted during the first part of 1993, that involved more than a hundred chemical engineering departments worldwide. Recent trends in CRE related to type of courses offered, teaching material, and textbooks used on both undergraduate and graduate levels, will be compared with the results of Dudukovic's previous survey.

QUESTIONNAIRE DESIGN AND ANALYSIS

The main objective of the survey was to determine what is taught as CRE at both the undergraduate and the graduate level in chemical engineering departments in North and South America, Europe, the Middle East, Asia, and Australia. A questionnaire was designed that included two main streams of questions: the first part consisted of eight questions and was primarily concerned with teaching and organization of the undergraduate and graduate courses; the second part dealt principally with the main and reference textbooks and the level of satisfaction with current teaching material, including the type of PC software packages. At the end of the questionnaire the departments were asked to give their perception of the

Mazen A. Shalabi received his BS and MS degrees in Chemical Engineering from Cornell University and his PhD in Chemical and Petroleum Refining from Colorado School of Mines. His major research interests are heterogeneous catalysis, kinetic modeling, and chemical reaction engineering.

Muhammad Al-Saleh received his BS and MS in Chemical Engineering from King Fahd University of Petroleum & Minerals, and his PhD from Colorado School of Mines. His current interests include catalysis, reaction engineering, and electrochemical reaction engineering.

Jorge N. Beltramini has taught undergraduate and graduate courses in thermodynamics, reaction engineering, catalysis, and mass transfer for more than fifteen years. His areas of interest cover petroleum refining, petrochemical processes, and environmental catalysis.

Dulaihan K. Al-Harbi received his BS and MS degrees in Chemical Engineering from the Pennsylvania State University and his PhD in Chemical Engineering from Oklahoma State University. His current interests include thermodynamics, transport properties, and fluid flow.

© Copyright ChE Division of ASEE 1996

future of CRE education for the next ten years.

A total of 137 questionnaires were sent out: 58 to U.S. chemical engineering departments and 79 to the other world areas mentioned above. The response rate was roughly 69%, with returns from 40 US departments and 55 from the other countries.

COURSE CONTENT

Figure 1a shows the number of CRE courses available for undergraduate students. The majority of schools have only one compulsory course (66%) while only 35% have at least one elective undergraduate course. This finding is similar to Dudukovic's survey of thirteen years ago showing that 69% of the schools had at least one CRE course available. On the other hand, Figure 1b shows that 42% of the schools have only one compulsory course for graduate students, compared to 64% thirteen years ago.

Figure 2 compares the distribution of undergraduate CRE courses (compulsory and elective) with the geographical distribution of the chemical engineering departments around the world. A very different distribution can be seen in the case of compulsory courses (Figure 2a). In the US, nearly 90% of the schools have one compulsory course, while in the United Kingdom practically all the

schools have two compulsory courses. A similar trend is observed in Asian countries, with 77% of the schools having two compulsory courses. On the other hand, nearly 20% of the continental European schools do not have compulsory courses at all. For the other regions (Middle East, Canada, Australia, New Zealand, and South America), the course distribution is between one and two compulsory courses, ranging from a minimum of 30% (Middle East) to a maximum of 75% (Canada) for one compulsory course. With reference to elective courses, the figure shows that with the exception of South American countries, there is an average tendency of 50% for not offering an elective course in CRE, with a minimum of 25% for Asian countries and a maximum of 80% for the United Kingdom.

With regard to the average class size for undergraduate

courses, most of the departments (51%) have classes of forty or more students (see Figure 3a), while only 5% have classes of less than twenty students. The majority of departments (75%) offer two to three hours of lecture per week (see Figure 3b), but it is important to note that 51% have less than two hours tutorial/problem solving per week, as shown in Figure 3c. Figure 3d summarizes the answers to a question regarding the number of laboratory experiments:

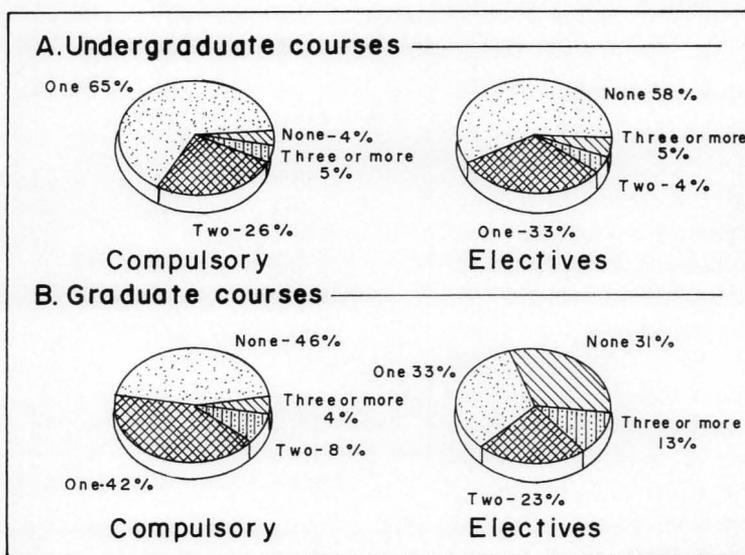


Figure 1a,b. Number of CRE courses available for undergraduate and graduate students.

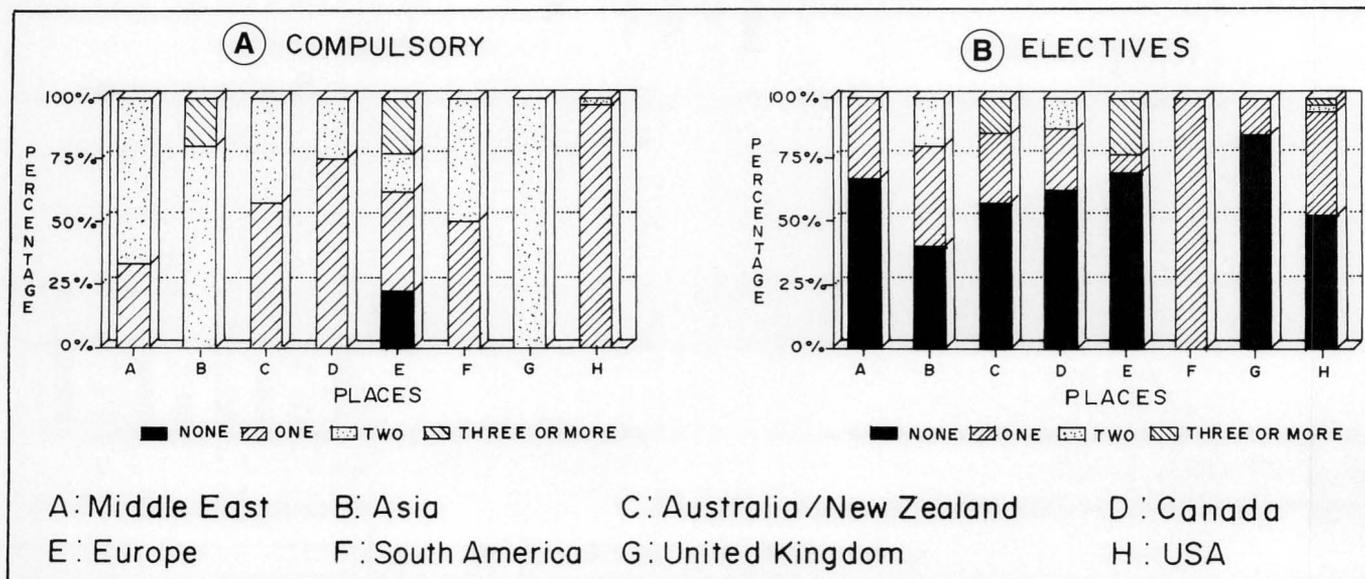


Figure 2a,b. Worldwide distribution of undergraduate CRE courses.

it can be seen that only 12% of the departments require at least one experiment during the teaching of the CRE course, and that 46% of the departments have no laboratory experiment.

Figure 4 compares class structure as a function of geographical distribution of the schools. Regarding class size, two well-defined groups were observed. One group, the Middle East and South American countries, have small classes (up to thirty), while the rest of the world accommodates larger classes (forty or more). Concerning time spent on lectures during the week, Figure 4b shows equal distribution for all locales, with two to three hours a week devoted to lectures. But there is ample disparity in the time distribution for tutorials per week as well as in the number of experiments performed, as can be seen in Figures 4c and 4d, respectively. Analysis of the data concerning the number of experiments performed (Figure 4d) shows that 70% of all the Middle East and US schools do not have experiments, but that 25% of the South American schools have at least one experiment.

Table 1 summarizes the basic concepts covered during the undergraduate course. Kinetics and mechanism, along with interpretation of kinetic data, are regarded as the most important concepts by 54% of the schools, followed by ideal reactor design and catalytic reactor design, by 46% and 43%, respectively. Only 23% of the schools ranked the importance of non-ideal reactors. In general, the different departments expressed that homogeneous systems receive more attention than heterogeneous systems, but as many as 18% of the departments do not cover heterogeneous systems at all in the compulsory undergraduate CRE. As far as industrial input is concerned, 32% of the departments claimed it as a very important part of the course.

TEACHING MATERIAL AND RECOMMENDED TEXTBOOKS

Table 2 shows the textbooks used for both undergraduate and graduate CRE courses. Eleven known textbooks were listed in the survey.¹⁷⁻¹⁷¹ For undergraduate courses, Fogler's textbook is the most popular, presently used by 41% of the schools. This replaced Levenspiel's textbook, written 23 years ago, that once enjoyed a popularity of 58% but which is presently used by only 25.3% of the departments. It is interesting to note that nearly 10% of the departments use their own textbook. They claimed that this allows them to properly match the CRE undergraduate curriculum with their time and place needs. The main reason cited for the change to

Fogler's textbook was his structured approach to teaching CRE that involves problem solving and decision making techniques. Some of the departments also cited the material covering the emerging areas (microelectronics, biotechnology, and polymerization reactions) as a reason for changing. Still another reason for the change was the use of computer software in solving the prescribed textbook exercises.

For graduate courses, Froment and Bischoff's textbook is the most popular (33.7%), while nearly 27.3% of the schools actually produce their own teaching material. Most of the instructors (92% undergraduate,

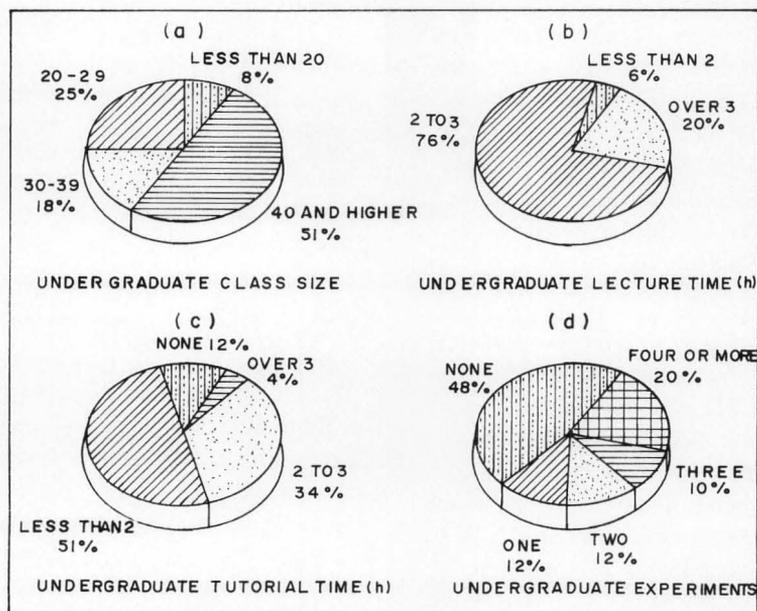


Figure 3. Class structure on undergraduate courses.

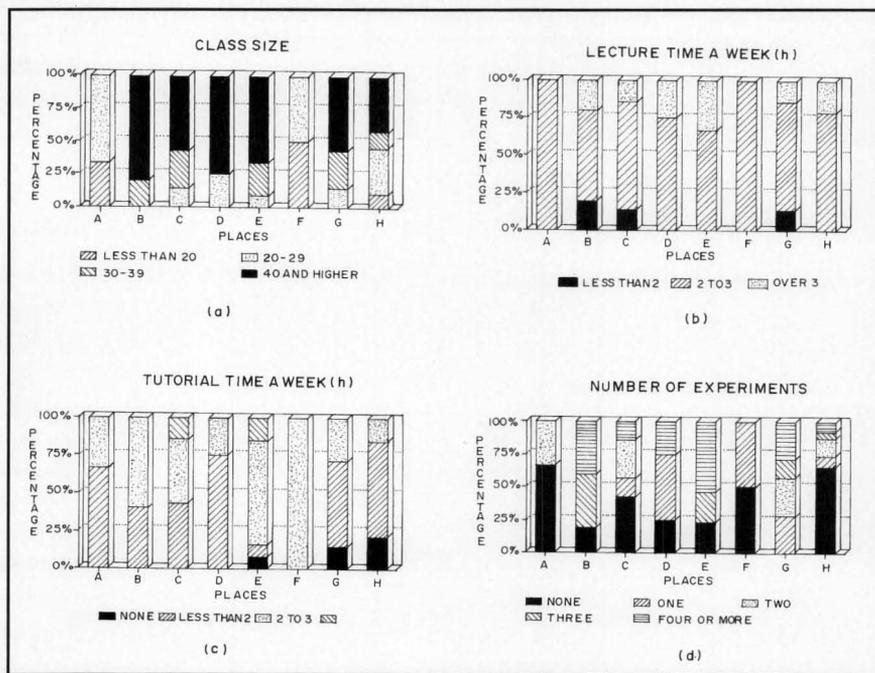


Figure 4. Class structure as a function of geographical distribution of the schools.

83% graduate) view their present textbook is satisfactory. Forty-four percent changed their textbook in the last five years, but only 25% of undergraduate and 18% of graduate courses are considering a change in the next two years.

Concerning development of software material for problem solving, 60% of the departments have developed or purchased computer software made available through main frame and personal computer facilities. The distribution by regions shows very clearly that in the case of US and Canada, 66% of the schools adopted this approach, while only 15% of the schools in Australia, New Zealand, South America, the Middle East, and Asia adopted it. In Europe and the United Kingdom, the percentage of positive answers was nearly 50%. The types of software ranged from commercial mathematical programs (such as Polymath and Mathematica) to more sophisticated software.

CURRENT AND FUTURE TRENDS

In answer to a question relating to the future of CRE courses in the next ten years, the following were the main points addressed by the departments:

- Of increasing importance would be computer applications and software packages, with the introduction of more computer-assisted problem solving and experimentation as well as modeling real reactor operations.
- More emphasis should be given to non-ideal reactors and to heterogeneous reactor design.
- Some aspects of heterogeneous catalysis should be covered in depth.
- Newer applications and technologies such as biochemical engineering, pollution control, and electrochemical reactors, should be introduced.
- More industrial examples with realistic data should be used.

SUMMARY AND RECOMMENDATIONS

In a field that covers such a large mix of possibilities, it would be presumptuous to list areas for continued or future attention. Even so, there are certain areas that have the potential for significant impact on the current and future chemical industry: catalysis and catalytic reaction engineering, solid state reaction engineering, mineral processing, etc.

ACKNOWLEDGMENT

The authors acknowledge the financial support of the King Fahd University of Petroleum & Minerals for the performance of this study.

REFERENCES

1. Doraiswamy, L.K., "Chemical Reaction Engineering: A Story of Continuing Fascination," *Chem. Eng. Ed.*, **26**(4), 184 (1992)
2. Savage, P.E., and S. Blaine, "Chemical Reaction Engineering Applications in Non-Traditional Technologies: A Textbook Supplement," *Chem. Eng. Ed.*, **25**(3), 150 (1991)
3. Vannice, M.A., "A Course on Heterogeneous Catalysis," *Chem. Eng. Ed.*, **13**(4), 164 (1979)
4. Miranda, R., "Heterogeneous Catalysis," *Chem. Eng. Ed.*, **23**(2), 166 (1989)
5. Dudukovic, M.P., "Survey of Chemical Reaction Engineering Courses," *Chem. Eng. Prog.*, p. 25, Feb. (1982)
6. Eisen, E.O., AIChE Report, "Teaching of Undergraduate Kinetics," 67th AIChE An. Meet., Washington DC (1974)
7. Smith, J.M., *Chemical Engineering Kinetics*, 3rd ed., McGraw-Hill (1981)
8. Levenspiel, O., *Chemical Reaction Engineering*, 2nd ed., Wiley and Sons (1972)
9. Fogler, S., *Elements of Chemical Reaction Engineering*, 2nd ed., Prentice Hall (1991)
10. Hill, Sr., C.G., *An Introduction to Chemical Engineering Kinetics and Reactor Design*, Wiley & Sons (1977)
11. Froment, G.F., and K.B. Bischoff, *Chemical Reactor Analysis and Design*, 2nd ed., Wiley & Sons (1990)
12. Carberry, J.J., *Chemical and Catalytic Reaction Engineering*, McGraw-Hill (1976)
13. Walas, *Reaction Kinetics for Chemical Engineers*, McGraw-Hill (1959)
14. Holland, C.D., and R.G. Anthony, *Fundamentals of Chemical Reaction Engineering*, 2nd ed., Prentice Hall (1978)
15. Cooper, A.R., and G.V. Jeffreys, *Chemical Kinetics and Reactor Design*, Prentice Hall (1973)
16. Denbigh, K.G., and J. Turner, *Chemical Reactor Theory: An Introduction*, 3rd ed., Cambridge University Press (1984)
17. Nauman, E.B., *Chemical Reactor Design*, Wiley and Sons (1987) □

TABLE 1
Course Dedication to Various Key Concepts in CRE

Topics	Very		Average	Not
	Important	Important		
Kinetics and mechanisms	54	28	15	3
Interpretation of kinetic data	54	33	13	-
Reactor design	46	21	30	3
Non-ideal reactors	23	44	32	1
Kinetics of catalytic systems	41	43	15	1
Diffusion and reaction in heterogeneous systems	40	35	21	4
Catalytic reactor design	43	39	18	-
Industrial oriented examples	32	40	26	2

TABLE 2
Undergraduate and Graduate Textbook Distribution

Textbook Author (ref)	Main Text		Reference Text	
	Undergrad	Grad	Undergrad	Grad
1. Smith, J.M. ^[7]	7.2	4.8	8.4	1.2
2. Levenspiel, O. ^[8]	25.3	8.4	27.7	7.2
3. Fogler, S.H. ^[9]	41.0	13.3	18.1	12
4. Hill, Sr., C.G. ^[10]	8.4	3	6	8
5. Froment, G.F./Bischoff, K.B. ^[11]	4.8	33.7	16.9	28.9
6. Carberry, J.J. ^[12]	0.5	5	8	8
7. Wallas, S.M. ^[13]	-	-	3.0	3
8. Holland, C.D./ Anthony, R.G. ^[14]	1.3	1.5	3.5	4
9. Cooper, A.R./Jeffrey, G.V. ^[15]	-	-	1	3
10. Denbigh, K.G./Turner, J.C.R. ^[16]	-	1.5	8	6
11. Nauman, E.B. ^[17]	1.5	1.5	2	6
Own Text	10.0	27.3	5.4	12.7

CHEMICAL ENGINEERING EDUCATION IN TURKEY AND THE UNITED STATES

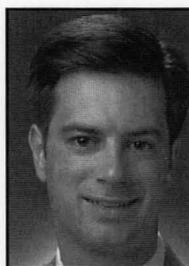
J. RICHARD ELLIOTT, JR.

The University of Akron • Akron, OH 44325-3906

A few years ago, Floyd^[1-3] wrote an interesting series of articles comparing the chemical engineering educational systems of the US and Japan. As an undergraduate at Tokyo Institute of Technology and a graduate student at the University of Wisconsin, he was able to identify a number of striking differences between the two systems. In this article, I would like to reconsider a number of Floyd's observations in relation to another country—Turkey. This presentation goes beyond Floyd's presentation in providing more systematic comparisons between the students' performances and backgrounds. The expectation is that seeing a number of educational systems juxtaposed in this way can lend some insight into the strengths of each system and suggest improvements for all.

According to Floyd, the most notable differences between the American and Japanese systems were related to the formidable entrance exams in Japan and the practice of attending intensive preparatory schools (“*junku*” in Japanese) during the period of secondary education. This intensive preparation evidently led to two significant outcomes: 1) greater preparation of the entering students made it possible to place much of the technical content earlier in the curriculum, and 2) a person's performance in college was less important than the college attended, so most of the college experience was considered as a time of rest (a kind of “relaxation” phenomenon). Since the Turkish system has a similar pre-college program (“*dershane*” in Turkish), one point of interest was to determine whether a number of Floyd's observations regarding the Japanese students might also be recognized in Turkish students.

There is a more broadly global justification for considering a country such as Turkey in relation to countries such as the US and Japan. If you made a list of all the countries with chemical engineering departments and sorted them according to gross domestic product per capita, the US and Japan



J. Richard Elliott is Associate Professor of Chemical Engineering at The University of Akron, where he has taught since 1986. He holds chemical engineering degrees from Penn State (PhD) and Va Tech (MS) and a BS degree in math/chemistry from Newport College. His interests are primarily in molecular thermodynamics and related applications. For the 1994-95 academic year, he served as a Fulbright Lecturer at Bogazici University in Istanbul, Turkey.

might not be considered as being globally representative.^[4] Countries such as India, China, and Argentina share measures like gross domestic product per capita more closely with Turkey than with the US or Japan. Thus, one might hope that the insights gained with respect to Turkey should reflect similar insights that might come from studying any one of many countries around the world.

This paper compares the curricula and, perhaps of most interest, characterizes the differences between the students by means of quantitative comparisons. Specifically, I have conducted the same course in thermodynamics at Bogazici University in Istanbul, Turkey, that I have taught for eight years at the University of Akron. A detailed description of my personal emphasis in this course was previously presented^[5] but, for the most part, this course represents a standard course in the chemical engineering curricula worldwide. Both sets of students used the same primary text and syllabus, had access to the same computational facilities, and faced identical examinations. By comparing performance on identical examinations simultaneously with other indicators of performance and background, a connection can be drawn between the local system and its overseas counterpart.

The essential computational resources were made available through the generosity of the Fulbright Program in that

they funded programmable calculators for every student in the Turkish course. Normally, Akron students are expected to purchase their own calculators with sufficient RAM (32 KB) to support programs for compressibility factor and departure function calculations as well as vapor-liquid K-ratios and bubble point pressure by the Peng-Robinson equation of state. The necessary programs are made available if the students purchase either a Sharp EL9300 or HP48G. Questions that are greatly facilitated by these programs are included on the tests and final exam. Through the Fulbright grant, all the Bogazici University students were provided with pre-programmed calculators that they could keep and carry to the exams. In the Turkish system, it is not typical for computational resources to be so integrated into the coursework at the undergraduate level, but, in order to give identical examinations, it was necessary that the computational resources be equalized to this extent.

BACKGROUND ON THE CURRICULA AND STUDENTS

The curricula of the schools are compared in Figure 1. The Bogazici University (BU) curriculum resembles the University of Akron (UA) to a higher degree than the Tokyo Institute of Technology (TI) curriculum. The TI curriculum reflects a considerably greater emphasis on general subjects and foreign languages. The major difference between BU and UA is that the BU curriculum places more emphasis on the specialization/research option than the UA curriculum, with a corresponding decrease in the general science emphasis. Both the TI and BU curricula place significant emphasis on the specialization/research option, whereas UA's research emphasis is relatively light. The most striking feature of the

This paper compares the curricula and, perhaps of most interest, characterizes the differences between the students [of Bogazici University and the University of Akron] by means of quantitative comparisons.

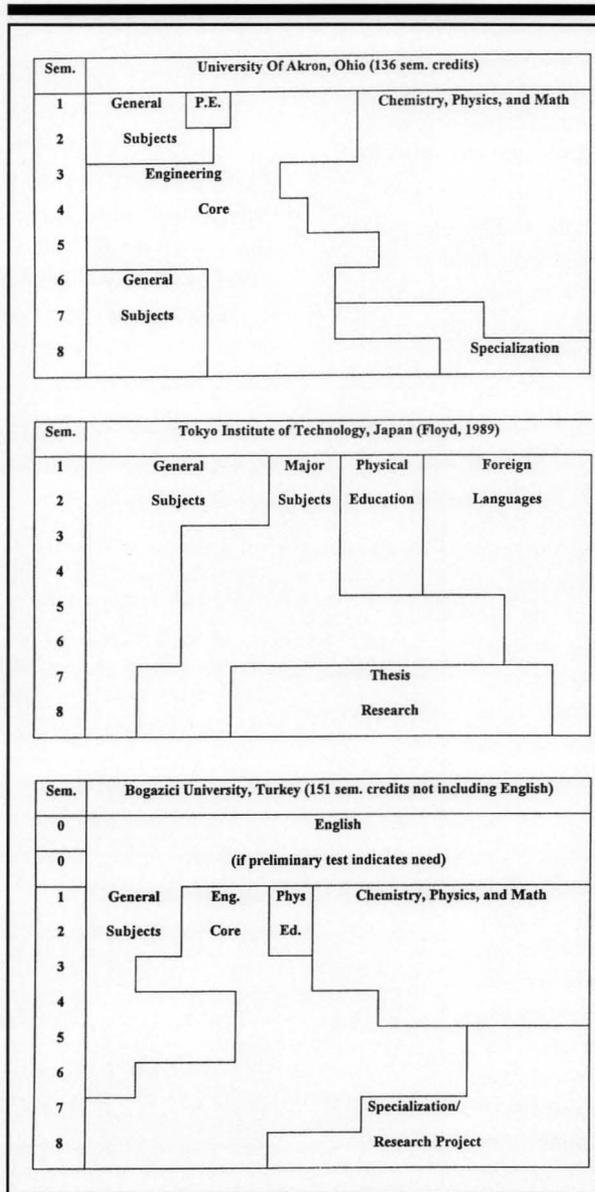


Figure 1. Outlines of undergraduate curricula.

UA curriculum is the high proportion of emphasis on general science courses. The emphasis on general science at UA limits the time available for specialization/research.

A detailed comparison of the courses shows that the BU students are required to repeat the freshman calculus, chemistry, and physics at the same level as their UA counter parts. This suggests that not every country takes advantage of the higher degree of preparedness of students admitted by a competitive national exam. One might suspect that calculus and physics are not covered on the BU national exam, but they are.

Another significant difference between the three curricula is the requirement of more total credit hours to graduate from an overseas university—151 at BU vs. 136 at UA. These extra credit hours are largely dedicated to industrial chemistry courses. The emphasis on industrial chemistry is similar to that in the TI curriculum, although it is not quite as intensive in Turkey.

Concerning the BU and UA curricula, a couple of slight curricular deviations are relevant to the thermodynamics course. The BU students take chemical engineering thermodynamics in the fall of the junior year vs. the spring of the sophomore year at UA. Furthermore, the BU students have had a full year of physical chemistry prior to the thermodynamics course. This deviation makes for a slight difference in the degree of preparedness of the students, beyond their pre-college backgrounds.

A small allowance was made for this difference by adjusting the grade scales, which will be discussed later.

It should be noted that BU has historical ties with the US educational system, especially in that all courses included in the four-year degree program are conducted in English. This

is also true of Middle East Technical University, another engineering school in Turkey with a substantial number of chemical engineering graduates. With this in mind, it is not too surprising that the BU and UA curricula are so similar.

As for the student backgrounds, entrance into BU is extremely competitive. Students indicate the schools and departments into which they would like to matriculate on their test papers. Students are matched with departments according to their performance on the exam and the availability of positions in each department. In a recent instance, of roughly 1,200,000 applicants taking the national entrance exams, the lowest score admitted to the BU chemical engineering program belonged to the 1400th student from the top (approximately the top 0.1% on average).

On the other hand, once admitted, all courses are practically free of charge, and it is somewhat difficult to fail a student from the curriculum. Furthermore, meals are subsidized, making housing the only significant expense after admission. To reduce housing costs, many students commute long distances, living with family members. It was suggested to me that the underlying student educational capacities should be roughly equivalent. The reasoning was that the UA students should be motivated by their more substantial tuition costs and fear of failure. BU students, on the other hand, should be predisposed to be successful based on the selection process for admission, but the advantage is somewhat nullified by the "relaxation" effect. It should be noted that most UA students pay the bulk of their tuition themselves, either through cooperative education or through part-time work.

Entrance to UA, like many US institutions, is not based on a competitive exam. America is known as the land of opportunity, and UA subscribes heartily to this proud tradition. Our admissions procedure is to admit virtually anyone who applies into the general program. Students may take courses in any curriculum until the junior level, by which time they are expected to achieve sufficient success to be admitted into a degree program or to continue sophomore courses until they can be admitted. A natural consequence of this admission policy is a relatively high attrition rate. To illustrate, our football coach was once challenged because only 60% of his athletes were graduating. After about a week of his fumbling around, someone informed him that 60% was nearly double the University average!

While the admissions policy and attrition rate at UA are subjects of some concern, it is not

entirely obvious how to devise an alternative policy that serves our mission of widely available public education. As for typical results in the chemical engineering department at UA, of 90 UA students initially registered for the sophomore course in material and energy balances in 1992, 40 eventually graduated. Approximately 120 students expressed an interest in chemical engineering at the freshman level and 60 students began the thermodynamics course (about 50% of those expressing interest at the freshman level). During a comparable period at BU, 50 students graduated while 55 students were admitted at the freshman level.

There are a number of other potential differences between the students and their backgrounds. To address these, the questionnaire in Table 1 was developed. The questions address issues such as commute times, part-time work hours, and course loads. The results from Table 1 suggest that UA students live away from their families and have shorter commute times and lighter course loads. They work part-time to about the same extent. According to Floyd, TI students tended

TABLE 1
Student Background Information Questionnaire

	<u>BU</u>		<u>UA</u>
1. The average time I spend commuting <i>from</i> home to school is ___ hours per day. Please do not count the return trip. I will do that.	0.7	avg (hrs)	0.3
	51%	% > 0.75	12%
2. At the beginning of the semester, I was working part-time ___ hours per week in addition to my engineering studies. (<i>e.g.</i> , private lessons/tutoring for pay, tour guide, McDonald's, . . .)	11	avg hrs among those working	9
	54%	% working	50%
3. I am taking ___ total course credits this semester.	19	avg	15
4. My cumulative grade point average including all courses <i>completed</i> to date is: ___/4.0	3.4	max	4
	2.4	mean	3.2
	1.3	min	2
5. I found the instructor's use of English to be a significant impediment to my learning this material relative to professors in my other classes. For example, he either spoke too fast or used vocabulary I could not understand, or in some other way spoke differently from my other professors such that my performance was impeded. <i>Agree • Somewhat Agree • Somewhat Disagree • Disagree</i>	20%	% agree or somewhat agree	13%
6. Mostly, I have been living with family members while attending school this semester. <i>True • False</i>	51%	% true	25%
7. Chemical engineering was not my first choice as a field of study, but it was the best I could do if I wanted to come to this school. <i>Agree • Somewhat Agree • Somewhat Disagree • Disagree</i>	56%	% agree or somewhat agree	13%
8. My career goal is to work my way out of engineering in the next five years and into some business or management position. <i>Agree • Somewhat Agree • Somewhat Disagree • Disagree</i>	70%	% agree or somewhat agree	31%

to share similar backgrounds with the Turkish students. The higher grade point averages among the UA students probably reflect a difference between the two educational systems. For example US students with lower averages would have sought another major by this stage in the curriculum. Even so, when considered in conjunction with the test results presented below, the difference in grade point averages suggests a significant degree of either grade inflation at UA or "de-

flation" at BU. Until recently, the math and science courses at BU have been the exclusive domain of engineering students. It seems possible that the teaching of these courses may have been designed to obtain a normal distribution in the grade scales that would be very different if the courses were offered to more diverse groups of students, as they are at UA.

It was surprising to learn that one of the BU students was working 42 hours per week (not counting the commute) and taking 21 course credits. The most similar UA student was working 30 hours per week while taking 13 course credits. BU faculty were generally surprised at the extent to which the students were working part-time. Another surprise was the number of BU students for whom chemical engineering was not a first choice—56% at BU vs. 13% at UA. The observation that 70% of BU students hope to work their way out of engineering in the next five years (31% for UA students) is perhaps related. Altogether, these results lend some insight into the manner by which a homogeneous selection of students still leads to a broad distribution in performance. The systematic placement of students into curricula that do not represent their first choice would seem to indicate a broad distribution in levels of motivation, especially considering that prospective employers rarely ask about the cumulative grade point averages of BU graduates.

GRADE SCALES AND PERCEPTIONS

One difference in the manner of conducting the two courses was the grade scale. Although the difference could influence the conclusions of this study, some differences were unavoidable and others were judged to be the best compromise between maintaining comparability between the two courses vs. adaptation to local influences. The most unavoidable difference was that the grade scale at BU was composed of fewer gradations. As shown in Table 2, there was only one intermediate grade between each whole grade level, instead of the A, A-, B+, . . . that exist at UA. Comparing the numerical values, it should be apparent that the whole letter grades were roughly matched at the A level (82 vs. 80), but there was a more significant deviation at the lower end of the scale. A 58 was a C at BU vs. a 50 for a C at UA. This difference might be expected to bias the BU grades to higher averages. On the other hand, the BU students had already taken physical chemistry and were juniors instead of sophomores. The minimum standards for such students should naturally be slightly higher. There was one other justification for this slight upward shift that had to do with what I refer to as a local influence. A sample of students revealed that 74% of students from BU graduated with two or more Ds on their transcript, vs. 19% at UA. Evidently, students at BU perceived a D less negatively than UA

students. This last observation provides support for the suggestion that BU students become complacent about their grades once they have been admitted.

RESULTS OF EXAMINATIONS

Figures 2 and 3 present the distributions of test scores at BU and UA. Table 3 presents summary statistics. The means at BU were significantly

TABLE 2
Grade Scales Applied at the Respective Universities

Bogazici University		University of Akron	
82	AA	A	80
76	BA	A-	75
70	BB	B+	70
64	CB	B	65
58	CC	B-	60
52	DC	C+	55
46	DD	C	50
		C-	45
		D	40

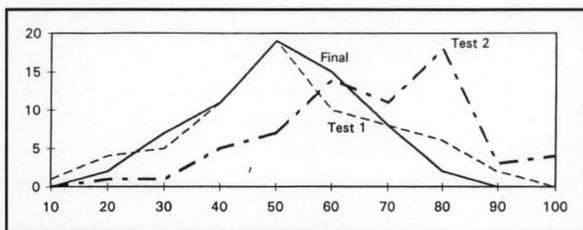


Figure 2. Frequency distribution plot based on test scores at the University of Akron.

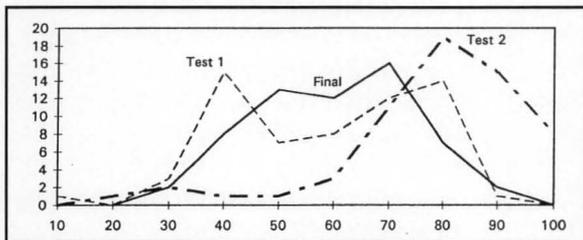


Figure 3. Frequency distribution plot based on test scores at Bogazici University.

TABLE 3
Summary Statistics for Tests at UA and BU

	University of Akron					Bogazici University				
	Min	Med	Max	Mean	Std Dev	Min	Med	Max	Mean	Std Dev
Test 1	4	45	85	47	18	0	53	89	54	18
Test 2	12	64	96	63	17	50	78	97	77	11
Final	13	48	81	47	16	20	55	85	55	15

higher than the means at UA at the 95% confidence level on all examinations. This seems to support the expectation that the more highly selected students should perform better. On the other hand, some influences apparently act to broaden the distribution of the highly selected group relative to the narrowness of the initial selection.

There are some differences between the groups of students that go beyond the summary statistics. The most striking difference is that the BU students went from a high-low bimodal distribution on the first test to a high unimodal distribution on the second test. As a result, the BU mean went from being seven points higher than the UA mean to fourteen points higher. Means at both schools were higher on the second test, indicating that it was a relatively easy test.

One interpretation of these observations would be that BU students needed to adapt to the new professor. On the other hand, I provided both groups with sample tests from the previous five years on both tests. Informal interviews with BU students who had made the switch indicated that the switching students had not studied the sample tests on the first test, but studied them seriously on the second test. The distribution on the second test and final were closer to what one would expect based on the differences in admissions policies. The UA test distribution was broader, reflecting a broader selection of admitted students.

It is interesting to note that a number of students achieved high scores at both schools, indicating that US schools are capable of producing top students despite the relatively low intensity during secondary education. Another observation about the differences relates to a qualitative observation about the way the students answered the questions. Over the years, I have become accustomed to writing the tests such that the more mathematical questions come at the end, because many of the UA students tend to have difficulty with these questions, but I noticed that the BU students tended to solve the test questions in reverse order (the first page was often left blank). It seems that the difference in the means on the second test is largely attributable to the difference in performance on the last question (worth 20 points on each test). This would concur with the other anecdotal observations about the stron-

ger mathematical backgrounds at foreign schools. Copies of the test questions can be obtained by contacting the author.

CONCLUSIONS AND RECOMMENDATIONS

The transition from making observations to making recommendations regarding such evolved educational systems is very delicate. The observations are never complete, and the recommendations often require personal judgements that may conflict with those of others. Noting these limitations, I have attempted to present the data completely in the preceding sections, such that alternative interpretations are not precluded. On the other hand, engineering estimates occasionally require making the best recommendation based on the limited data at hand—this is the spirit of the recommendations below.

My most significant impression was that a substantial fraction of the BU students were underachieving. This impression derives primarily from talking with students who were having difficulty and learning that their problems related simply to a lack of study. The reasons why this might happen are reflected by the fact that most of them are not really interested in chemical engineering and because administrative practices and employment prospects are less motivating than those experienced by UA students. The BU administrative system makes it very difficult for them to fail and discourages transfer to other majors. Prospective employers show little interest in what grades the students have obtained; their primary interest concerns from which school the students have graduated. Tuition is free, so there is little penalty for taking extra time to graduate. Entirely different attitudes prevail for the UA students on each of these scores.

Many of these issues are beyond the control of the faculty, but faculty can influence the curriculum in a way that might help to balance their negative impact by integrating the students' motivations into the overall plan. Regarding the curriculum at BU, it seems that the nature of the students' backgrounds and interests are not taken into account with optimal efficiency. Calculus, physics, and chemistry are required elements of the national entrance exam. Students scoring in the top 0.1% on this exam can be assumed to know something about these subjects, but the

*... this
[thermodynamics]
course represents a
standard course in the
chemical engineering
curricula worldwide.
Both sets of students
used the same primary
text and syllabus, had
access to the same
computational
facilities, and faced
identical
examinations. By
comparing
performance on
identical examinations
simultaneously with
other indicators of
performance and
background, a
connection can be
drawn between the
local system and its
overseas counterpart.*

curriculum begins with these subjects in direct emulation of its US counterpart. Anecdotal reports indicate that these courses tend not to enhance the students' attitudes towards learning.

Shortcomings at such an early stage in the college curriculum reinforce attitudes deriving from the "relaxation" effect occurring after the intense preparation to pass the entrance exam. My recommendation is that the BU curriculum be revised to reduce the required credit hours in freshman chemistry, physics, and mathematics. Students should begin these subjects at the sophomore level, similar to the Japanese students. Such a step would bring the total number of required courses much closer to the 15 credit/semester level.

At the same time, a strict limit should be applied on the number of credits that a student is allowed to take if his cumulative grade point average drops below 2.25. A computer program should be implemented to enforce this limit since human nature is not always reliably strict. Such a simultaneous give-and-take should have the effect of emphasizing quality over quantity in a way that would be purely beneficial.

As for the organization of the curriculum, the large number of BU students who expect to be out of engineering in five years would seem to indicate a need for some innovation. It is easy to proclaim that engineering instruction is the only proper domain of engineering educators, but my experience has been that motivated students are more effective learners. Furthermore, the interests of the students may reflect a practical perception of the opportunities available in the local job market. Such practical considerations should be of interest to the engineering educator.

Is it possible that the same engineering content could be covered while recognizing the motivations of the students? I believe it is possible, and I would like to outline one example of how it might be achieved. Most of the investment economics, costing, optimization, and safety aspects of the traditional senior design course require little knowledge that is limited to senior status. There is no reason why the bulk of this coursework could not be moved to the sophomore year at the latest. Since the students are primarily motivated by the business aspects of engineering, such a move would bolster their interest levels at a time when they might still be positively influenced. Given such a background at an early stage, incorporation of business-oriented projects into the remaining curriculum would be greatly facilitated. This is one example of how adaptation to the local educational environment can be achieved with little practical penalty, and I expect that many more could be conceived.

As for the UA students, it is encouraging that the best

UA students were not significantly disadvantaged relative to the BU students. This means that their pre-college preparation was not entirely disabling. On the other hand, there were a number of students in the UA thermodynamics class who were not competitive at the international level. This observation reaffirms the need for maintaining significant minimal performance standards in the UA curriculum and, perhaps, indicates a need to raise them slightly. Furthermore, the emphasis on pre-college preparation often cited by engineering and science educators, especially with regard to math skills, should be reiterated. The self-determination of the UA system offers the advantage of more motivated engineering students, but the reduction in the level of technical preparation at the pre-college level should not be ignored.

More generally, US faculty should recognize some differences in chemical engineering education as practiced in other parts of the world. One benefit of such a global perspective is in helping to understand the educational developments of many of the students who come to the US for graduate school. About 10% of BU graduates pursue graduate school abroad. By understanding the environments in which students were brought up and how they differ from the US environment, it should be possible to develop favorable interactions more quickly and easily.

At the undergraduate level, the greater emphases on industrial chemistry and undergraduate specialization/research are common to Japan and Turkey at least. We should ask ourselves whether there might be some validity in emphasizing these topics to a greater extent in US curricula. ABET's emphasis on enhancing the "design content" of chemical engineering curricula is somewhat similar to the manner in which schools overseas are already practicing. We should also question the significance and implications of grade inflation in the US.

Finally, US professors must exhort themselves to produce globally competitive graduates in spite of all obstacles. The evidence shows that fairly average but highly motivated undergraduates are capable of nearly catching up with others who are highly selected. Apparently, there are advantages to a fairly broad admissions policy that should not be discounted.

REFERENCES

1. Floyd, S., *Chem. Eng. Ed.*, **22**, 144 (1988)
2. Floyd, S., *Chem. Eng. Ed.*, **22**, 218 (1988)
3. Floyd, S., *ChemTech*, **19**, 422 (1989)
4. The gross domestic product per capita of Turkey is roughly \$3400, whereas the comparable amount in the US is roughly \$22,000. These are 1991 figures taken from *Grolier's Encyclopedia* on CD ROM (1994)
5. Elliott, J.R., *Chem. Eng. Ed.*, **27**, 44 (1993) □

UNDERGRADUATE ACADEMIC ADVISING

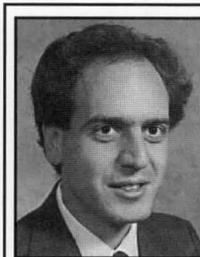
MICHAEL L. MAVROVOUNIOTIS

Northwestern University • Evanston, IL 60208-3120

The balance between research and teaching has been the subject of considerable analysis in the past few years, but less attention has been paid to another important component of academic activity: academic advising. It is easy to overlook the significance of advising and classify it as a support activity with only a minor role in the educational effort compared to the central role of classroom teaching. But if a poorly advised student is in the wrong major or the wrong class, given his or her talents and desires, then even the best classroom teachers are sowing their seeds on poor soil.

Advising also has an impact under less dramatic circumstances: If students do not understand the role of a class for their needs and goals, they would be taking the right class for the wrong reasons and would likely lack the motivation to do well. In short, advising can be an invisible hero allowing classroom teaching to bear the most fruit, or a villain acting as an obstruction and inhibitor to classroom learning.

There is a variety of competing theories and strategies for middle-school or high-school advising,^[1] but literature on the advising role of faculty in undergraduate education (let alone *engineering* education) is rather limited, and some of it addresses only specific subareas, such as women's issues,^[2] undecided students,^[3] morality, prejudice, and mental health,^[4] and it tends to target counseling or student-affairs offices rather than university faculty advisors. There is, nevertheless, some useful (and essentially unanimous) guidance in the literature. Winston and his coworkers have presented a comprehensive treatment of undergraduate academic advising^[5] as well as a succinct practical guide.^[6] Other sources include an early report published by the National Education Association^[7] and more recent handbooks by Gordon^[8] and by Kuh.^[9] This brief article presents some of the observations and recommendations made in these sources along with the author's own views and experiences.



Michael Mavrovouniotis is Associate Professor of Chemical Engineering at Northwestern University. He received his Diploma of Engineering from the National Technical University of Athens (Greece) in 1984 and his PhD from the Massachusetts Institute of Technology in 1989. Prior to joining Northwestern in 1993, he served on the faculty of the Institute for Systems Research and the chemical engineering department at the University of Maryland, College Park.

IMPORTANCE OF ACADEMIC ADVISING

Academic advising is an integral part of the educational process, not just a support service. Effective advising programs offer students an opportunity to realize their full potential.^[5] The educational process and the goals it serves are complex and confusing to most undergraduate students. The tremendous opportunities offered by a university education, with all their ramifications for the rest of the student's life and career, can easily be missed or under-used. As the student is coping with the complex university environment it is easy for him to focus on minor details and daily duties rather than on his personal and educational development. The advisor's office, with its many systematic student contacts, is a powerful mechanism for implementing intentional and deliberate student development.^[6]

Academic advising has an impact on students' retention, academic success, and the career-choice process.^[6] Its influence and significance are much greater than its duration would suggest because it occurs at critical points when the advisee is faced with crucial decisions—decisions which can be facilitated by the professional experience and personal maturity of the advisor.

Unfortunately, many present-day advising programs operate as bureaucratic, clerical activities on the periphery of effective educational services.^[6] With the growth in univer-

sity enrollments in recent years, academic advising seems to have become a victim of the rush to admit greater numbers of students. As a result, the nature of students' educational experience has been profoundly affected.^[5] Surveys of students and college administrators alike reveal general dissatisfaction with both the quality and the effectiveness of academic advising on most college campuses.^[5]

ADVISING ROLES AND MODES

There can be considerable variation in advising modes. The *prescriptive* advisor is one who focuses on student limitations.^[8] Students are assumed to be naturally immature and irresponsible, and thus the educational pace, mode, and direction are controlled by the advisor. *Developmental* advisors, on the other hand, concentrate on students' potentialities and view students as striving, responsible, and capable of self-direction. The advisor's role in the prescriptive approach is one of authority and judge. The developmental advisor's role is one of helper and interactive teacher.^[8]

There are limits to an advisor's responsibility to the students, and students must learn what these limits are. How intrusive should an advisor be? At one extreme, one might declare that students are adults who can read the catalog and therefore should make their own academic decisions; this reduces the advisor to a rubber-stamping role. The other extreme is to be in constant contact with students about every detail and technicality of every decision they make. There is an appropriate middle path in developmental advising. Advisors may try to motivate the students through encouragement and support, but the responsibility for taking action is the student's.^[8] Kramer and Gardner^[7] cite the advisee's "right to fail." Ultimately, the advisee makes decisions and assumes responsibility; the advisor should alert the student to potential consequences, but should accept the student's decisions even when they appear unwise and may lead to failure.

Kramer and Gardner offer an expanded classification of advisor roles, emphasizing that the roles shift depending on the particulars of the advising question and on symmetric roles assumed by the student. The advisor's role might be one of

- *An adult (signifying age, experience, and maturity)*
- *An expert (possessing mastery of subject matter area through training and achievement)*
- *A teacher (charged with transmission of skills and information)*
- *A researcher (investigator, explorer)*

It is easy to overlook the significance of advising, often viewed as a support activity with only a minor role in the educational effort compared to the central role of classroom teaching . . . [but] advising can be an invisible hero allowing classroom teaching to bear the most fruit, or a villain acting as an obstruction and inhibitor to classroom learning.

- *A friend (offering emotional and personal attachment; confidant)*
- *A judge (carrying out evaluation, assessment, arbitration, criticism)*
 - *An authority (possessing prestige and power, giving orders and directions)*
 - *A rubber stamp (confirming and agreeing with any position presented)*
 - *A lecturer (offering systematic and formal instruction to a body of knowledge)*

The advisor's response to a simple and common encounter can come from any of these roles. For example, when the student comes in with a drop slip and the request, "I want to drop a course," the advisor may check the rules on what courses may be dropped and when, or simply sign the slip and let the registrar figure out the legalities.^[7] Or, starting from the roles of teacher and friend, the advisor can set the administrative aspects of the request aside and try to find out what has prompted the student to make the request and whether a change in the student's long-term plans is under way (or may be needed). Misconception of roles between student and advisor is very common. To avoid miscommunication, it is important to clarify what role the student expects you to assume^[7] and either assume that role or adjust the student's expectation.

CHANGING THE SYSTEM: SEPARATION OF TASKS

In an epilogue to their excellent book, Winston and co-workers offer a model for effective, efficient, and attentive academic advising.^[10] One of their recommendations is the separation of the clerical, record-keeping side of advising from interpersonal and intellectual guidance.

Advising programs that emphasize registration and record keeping, while neglecting attention to the student's educational and personal experiences in the institution, are missing an excellent opportunity to directly and immediately influence the quality of a student's education. Such programs are also highly inefficient^[10] since they are most likely employing highly educated (expensive) personnel who are performing what are essentially clerical tasks. It is easier to set the right priorities for the faculty's involvement in advising if the process of academic advising is separated from class scheduling and registration. In many instances, class scheduling masquerades as academic advising, which explains why many in higher education view academic advising as simply an administrative chore.

In Winston's model, class scheduling and registration are to be accomplished by student paraprofessionals who are closer to the process than most advisors can or desire to be. Student paraprofessionals and support staff are more likely to master the mechanics and nuances of the registration process than are advisors who have other priorities to attend to, such as class preparation, research, and strategic administrative tasks. This neatly separates the developmental side of advising from the naturally prescriptive administrative side and allows the faculty advisor to more fully play the role of teacher rather than authority.^[8] An alternative to this systemic change is for a faculty advisor to cluster the clerical side of advising to a single meeting with all of his or her advisees.^[11]

The obvious risk in the separation of tasks may be less frequent contact between students and advisors. Students may consider contact with faculty unnecessary if the bureaucratic side of advising is handled elsewhere. Even faculty might come to regard exclusively developmental advising sessions as low-priority items, easily squeezed out of the faculty's schedules and attention. Thus, an important prerequisite for beneficial separation of tasks is that both faculty and students must come to regard regular advising contact as essential.

WHAT THE INDIVIDUAL ADVISOR CAN DO

The most important action on the side of the individual advisor is to adopt the developmental approach. Unfortunately, without the systemic change cited above, there is a certain incongruity between the developmental role and university regulations, since the advisor usually has the authority to approve or deny student requests and is responsible for ensuring that degree requirements are met. But great strides can be made by encouraging students themselves to master some of the nuances in the regulations, by explaining broader options and consequences, and by respecting the student's decisions. Naturally, lower-division students are less likely to be independent and responsible decision makers, and the advisor may need to be more proactive and leave somewhat less freedom to the students.^[11] This is understandable, and the advisor should provide the necessary guidance while gradually pushing the students toward more control and responsibility.

There is often incongruity between the student's and the advisor's perceptions of the process,^[8] so it is important to instill the developmental approach in the student. For example, students are often extremely reluctant to "take up your valuable time" if they perceive advising only in its prescriptive and clerical side. Such a consideration is not to be downgraded, but if you are interested in offering your assistance in developmental advising, it is important to convey to advisees your willingness to engage in conversation and consultation.^[7]

LEARN THE CULTURE OF YOUR STUDENTS

The influence of the culture of institutions and student groups on the educational experience is substantial.^[9] Each educational institution has its own culture, but there is often little intersection between the faculty subculture and the (undergraduate) student subculture. An advisor's entire interaction with students improves as the advisor gains familiarity with the culture the students are immersed in. It is, admittedly, not easy to learn the student side of the institutional culture, but even a general awareness of student life, customs, and habits is helpful;^[9] simple steps, such as reading the student newspapers (few faculty do!), are a good start. The process has an obvious autocatalytic character since, as you learn more, your interactions with students become easier and give you a clearer view of their culture.

Depending on how (in)homogeneous your institution is and how unusual your advisees, advising effectiveness might even require familiarity with specific student subcultures, groups, or activities. It is not uncommon for advisees' academic problems to be related to the study habits of living groups.^[9] If one of your advisees is on the swimming team, make it a point to follow the results of the swimming competitions and find out a little about the students' travel and training schedule (you will discover that swimmers train every day for about four hours, or until they are completely exhausted).

On the subject of culture, Kuh^[9] offers several pieces of advice directed to student-affairs professionals, but clearly relevant for faculty: know thyself—your values and assumptions; discover the various student cultures on campus; use cultural perspectives for diagnosis and analysis; recognize the importance of living areas and affinity groups to student culture; be wary of attempts to systematically change student culture, but recognize that student cultures can be changed; use cultural perspectives when working with marginal groups.

STRUCTURE OF THE ADVISING SESSION

In routine advising sessions, whether associated with registration or not, my own strategy is to simply review progress-to-date and the future plans of the student, trying to learn a bit more about the student's talents and goals with every session. The following simple structure is adequate—provided that the advisor follows up on student answers with genuine interest, useful observations, and information that helps the student place the modest academic issues in the greater context of her education and career.

- ▶ First, take care of the administrative details rather briskly, making sure they don't consume the entire meeting. Some of the administrative matters can be used as entry points to probe the student's academic and career interests during the rest of the meeting.

- ▶ The second step is to ask some questions on the advisee's recent work: Which classes did the student like or dislike last quarter and why? Were there any unexpected academic difficulties or achievements in recent classes?
- ▶ After assessing the past and present, ask for the student's thoughts on educational plans such as specialization areas and career paths. Offer guidance on feasibility and good means for achieving the student's goals—such as course choices or internships. Mention other opportunities the student may have overlooked or may be misinformed about, such as graduate or professional education.
- ▶ Encourage the student to get second opinions on major issues. Suggest other faculty, university offices, or other information sources.

In those cases where the student comes for a special consultation, the following generic structure, adapted from an outline given by Gordon,^[8] can be used for the advising session.

1. Opening the Interview

- Show openness, interest, and concentrated attention.
- If possible, obtain the student's folder or record so that relevant information is available during the interview.

2. Identifying the Problem

- Ask the student to state the problem, helping the student articulate, if needed. Gather as much information as possible by prompting the student to provide all relevant facts.
- Is the problem presented by the student actually covering a different real problem? Ask open-ended probing questions.
- Is the student presenting several problems? Ask the student to isolate the primary foremost concern. Multiple problems may have a single root cause that should be identified, or the student may be so troubled by one issue that he or she takes a gloomy view that makes lots of secondary issues appear as equal obstacles.
- State your interpretation of the problem and give the student a chance to clarify, elaborate, or correct your interpretation.

3. Identifying Possible Solutions

- Ask the student for his or her ideas on solving the problem. Help the student generate additional

alternative solutions.

- Discuss the mechanics of each solution (what, how, when, who). Discuss implications of each solution. Will a solution create conflicts with other plans?

4. Taking Action on the Solution

- Plan a specific order and time frame for action steps, including procurement of additional information and referrals to other university resources or offices. The advisor should have handy referral information on a variety of campus offices and resources.
- Plan follow-up by the student and/or the advisor.

5. Summarizing the Transaction

- Review what has transpired and restate action steps.
- Encourage future contact; make a definite appointment for review if necessary.
- Once the student departs, summarize the transaction for your own notes or for the student's file.

While the above structure is appropriate for most advising sessions, the duration of the session can vary a great deal. In my own experience, ten minutes is the bare minimum for any session, no matter how trivial the problem. A simple answer to a student dropping in with a simple question only takes a minute or two, but there are two reasons for taking longer. First, in the interest of cultivating the relationship and ensuring that the student will not hesitate to seek future contact, the advisor should take the time to make the student feel at ease, inquiring about other advising issues or the student's interests; it takes ten minutes to demonstrate your interest in the advisee. Second, it is important for the advisor to explore the origin of the question and whether it is related to other obstacles the student is faced with but has not brought up. Naturally, advising sessions dealing with complex issues, such as specialization and career paths, will take much longer than this minimum and may have to be broken down into a series of meetings; in such cases, at the end of each meeting the student should always be left with a set of questions to ponder for the next meeting.

The commonplace use of electronic mail by faculty and students provides an alternative efficient way to answer simple questions without appearing hurried or damaging the advisor-student relationship. If more discussion is nevertheless warranted, the advisor can respond with an offer for an appointment, which is easily arranged by e-mail.

In the opposite extreme, a note of caution is in order; serious problems of a nonacademic nature (even if brought about by academic events) occasionally arise (*i.e.*, severe depression, thoughts of suicide, substance abuse, acute inter-

personal problems among students). The engineering faculty advisor is unlikely to possess the requisite special training and skills to deal with such issues effectively, and a well-intentioned attempt to help might even worsen the problem. It is best to refer such problems to trained counselors available at any university. To make sure that the student receives help, the advisor may insist that an appointment be made right then and there. Afterward, the advisor should follow up with the counseling office to make sure that the student kept the appointment, as well as check with the student periodically so the student knows someone is concerned. In order to deal with such crises, the advisor should be aware of all the relevant campus resources, along with contact names and phone numbers—before any crisis occurs.

CONCLUSION

The central premise of this article is that the advising process is an integral part of the educational process. Unfortunately, it is too often misinterpreted as a purely clerical task and receives only limited attention by the faculty, students, and administration. A valuable systemic change would be the separation of the clerical and developmental sides of advising; the former can be handled by staff, allowing the faculty's full attention to be devoted to the intellectual growth of the students.

Faculty advisors should strive to improve the strategies they follow in encouraging student contact, acting in a teaching and supportive role, allowing the students ultimate decision-making and responsibility, and helping students to focus on the greater educational and professional decisions and objectives and the means for accomplishing them.

ACKNOWLEDGMENTS

The author wishes to thank Professors Richard Felder, John O'Connell, Christopher Bowman, William Miller, and Julio Ottino for their comments, which guided a substantial revision of this paper.

REFERENCES

1. Myrick, R.D., L.S. Myrick, and contributors, *The Teacher Advisor Program*, ERIC Counseling and Personnel Services Clearinghouse, Ann Arbor, MI (1990)
2. Gelwick, B., ed., *Up the Ladder: Women, Professionals, and Clients in College Student Personnel*, American College Personnel Association, Cincinnati, OH (1979)
3. Gordon, V., *The Undecided College Student: An Academic and Career Advising Challenge*, Charles C. Thomas, Springfield, IL (1984)
4. Farnsworth, D.L., and G.B. Blaine, Jr., eds., *Counseling and the College Student*, Little, Brown, and Co., Boston, MA (1970)
5. Winston, R.B., Jr., T.K. Miller, S.C. Ender, T.J. Grites, and associates, *Developmental Academic Advising: Addressing Students' Educational, Career, and Personal Needs*, Jossey-Bass Publishers, San Francisco, CA (1984)
6. Winston, R.B., Jr., S.C. Ender, and T.K. Miller, eds., *Developmental Approaches to Academic Advising*, Jossey-Bass

Publishers, San Francisco (1982)

7. Kramer, H.C., and R.E. Gardner, *Advising by Faculty*, National Education Association, Washington, DC (1977)
8. Gordon, V.N., *Handbook of Academic Advising*, Greenwood Press, Westport, CT (1992)
9. Kuh, G.D., ed., *Cultural Perspectives in Student Affairs Work*, American College Personnel Association, Cincinnati, OH (1993)
10. Winston, R.B., Jr., T.J. Grites, T.K. Miller, and S.C. Ender, "Epilogue: Improving Academic Advising," in *Developmental Approaches to Academic Advising*, R.B. Winston, Jr., S.C. Ender, and T.K. Miller, eds., Jossey-Bass Publishers, San Francisco, CA (1982)
11. Wankat, P.C., and F.S. Oreovicz, *Teaching Engineering*, McGraw-Hill, New York, NY, pp. 201-205 (1993) □

LABORATORY EXPERIMENT

Continued from page 101.

lem, particularly for the 1990s, it is based on well-tested combustion phenomenon and not limited to a special limited situation, and the data from the unit are not complete, forcing the soon-to-be practicing engineers to solve problems and perform an analysis based on their best judgment.

The experiment is best performed over an entire day, so trying to carry it out in a half-day session is not recommended. We strongly advise that the entire experiment be located in a fume hood so that the flue gas is swept out of the unit and no dangerous or noxious odors are emitted into the laboratory. Finally, the potential to overheat the fluid-bed unit from feeding too much fuel gas means that the students need to be monitored periodically to be sure they are operating the unit in a controlled and safe manner. The use of a high-temperature limit switch will eliminate this potential problem.

ACKNOWLEDGMENTS

KKR wishes to express his extreme appreciation to James Jaeger in Northwestern's machine shop for his help in machining and fabricating the fluid-bed unit. He also appreciates the technical information provided by George Rasmussen at Ecova for the incinerator design. Finally, the Northwestern Chemical Engineering Department wishes to express its thanks to Procter and Gamble Company for generously providing the funds for the development of this "hands-on" engineering experiment.

REFERENCES

1. Dahlstrom, D.A., "Chemical Engineering: Notes on Its Past and Its Future," *Chem. Eng. Ed.*, **28**(4), 226 (1994)
2. Hougan, Olaf A., "Seven Decades of Chemical Engineering," Bicentennial Lecture of Chemical Engineering History, AIChE 82nd National Meeting, Atlantic City, NJ
3. Bird, R. Byron, "Hougen's Principles," *Chem. Eng. Ed.*, **20**(4), 161 (1986)
4. Mullen, J.F., "Consider Fluid-Bed Incineration for Hazardous Waste Destruction," *Chem. Eng. Prog.*, **88**(6), 50 (1992) □

AUTHOR GUIDELINES

This guide is offered to aid authors in preparing manuscripts for Chemical Engineering Education (CEE), a quarterly journal published by the Chemical Engineering Division of the American Society for Engineering Education (ASEE).

CEE publishes papers in the broad field of chemical engineering education. Papers generally describe a course, a laboratory, a ChE department, a ChE educator, a ChE curriculum, research program, machine computation, special instructional programs, or give views and opinions on various topics of interest to the profession.

• Specific suggestions on preparing papers •

TITLE • Use specific and informative titles. They should be as brief as possible, consistent with the need for defining the subject area covered by the paper.

AUTHORSHIP • Be consistent in authorship designation. Use first name, second initial, and surname. Give complete mailing address of place where work was conducted. If current address is different, include it in a footnote on title page.

TEXT • We request that manuscripts not exceed twelve double-spaced typewritten pages in length. Longer manuscripts may be returned to the author(s) for revision/shortening before being reviewed. Assume your reader is not a novice in the field. Include only as much history as is needed to provide background for the particular material covered in your paper. Sectionalize the article and insert brief appropriate headings.

TABLES • Avoid tables and graphs which involve duplication or superfluous data. If you can use a graph, do not include a table. If the reader needs the table, omit the graph. Substitute a few typical results for lengthy tables when practical. Avoid computer printouts.

NOMENCLATURE • Follow nomenclature style of Chemical Abstracts; avoid trivial names. If trade names are used, define at point of first use. Trade names should carry an initial capital only, with no accompanying footnote. Use consistent units of measurement and give dimensions for all terms. Write all equations and formulas clearly, and number important equations consecutively.

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

LITERATURE CITED • References should be numbered and listed on a separate sheet in the order occurring in the text.

COPY REQUIREMENTS • Send two legible copies of the typed (double-spaced) manuscript on standard letter-size paper. Submit original drawings (or clear prints) of graphs and diagrams on separate sheets of paper, and include clear glossy prints of any photographs that will be used. Choose graph papers with blue cross-sectional lines; other colors interfere with good reproduction. Label ordinates and abscissas of graphs along the axes and outside the graph proper. Figure captions and legends will be set in type and need not be lettered on the drawings. Number all illustrations consecutively. Supply all captions and legends typed on a separate page. State in cover letter if drawings or photographs are to be returned. Authors should also include brief biographical sketches and recent photographs with the manuscript.

Send your manuscript to
Chemical Engineering Education, c/o Chemical Engineering Department
University of Florida, Gainesville, FL 32611-6005

CALL FOR PAPERS

FALL 1996
GRADUATE EDUCATION ISSUE OF
CHEMICAL ENGINEERING EDUCATION

Each year

Chemical Engineering Education

publishes a special fall issue devoted to graduate education.

It includes

- articles on graduate courses and research, written by professors at various universities,
and
- ads describing the university graduate programs.

Anyone interested in contributing to the editorial content of the 1996 fall issue should write to *CEE*, indicating the subject of the contribution and the tentative date it will be submitted.

Deadline is July 1, 1996.