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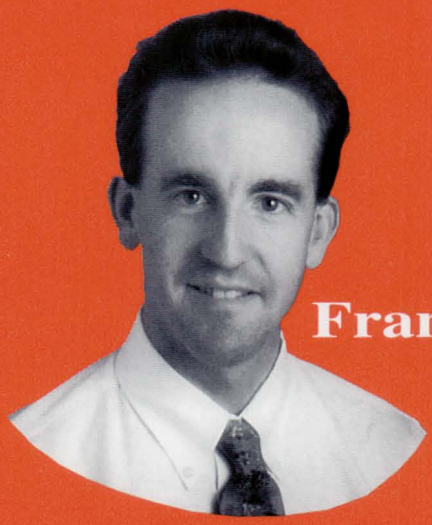

Frank Doyle III

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...and chemical engineering at

Worcester Polytechnic Institute

Chemical Engineering Education

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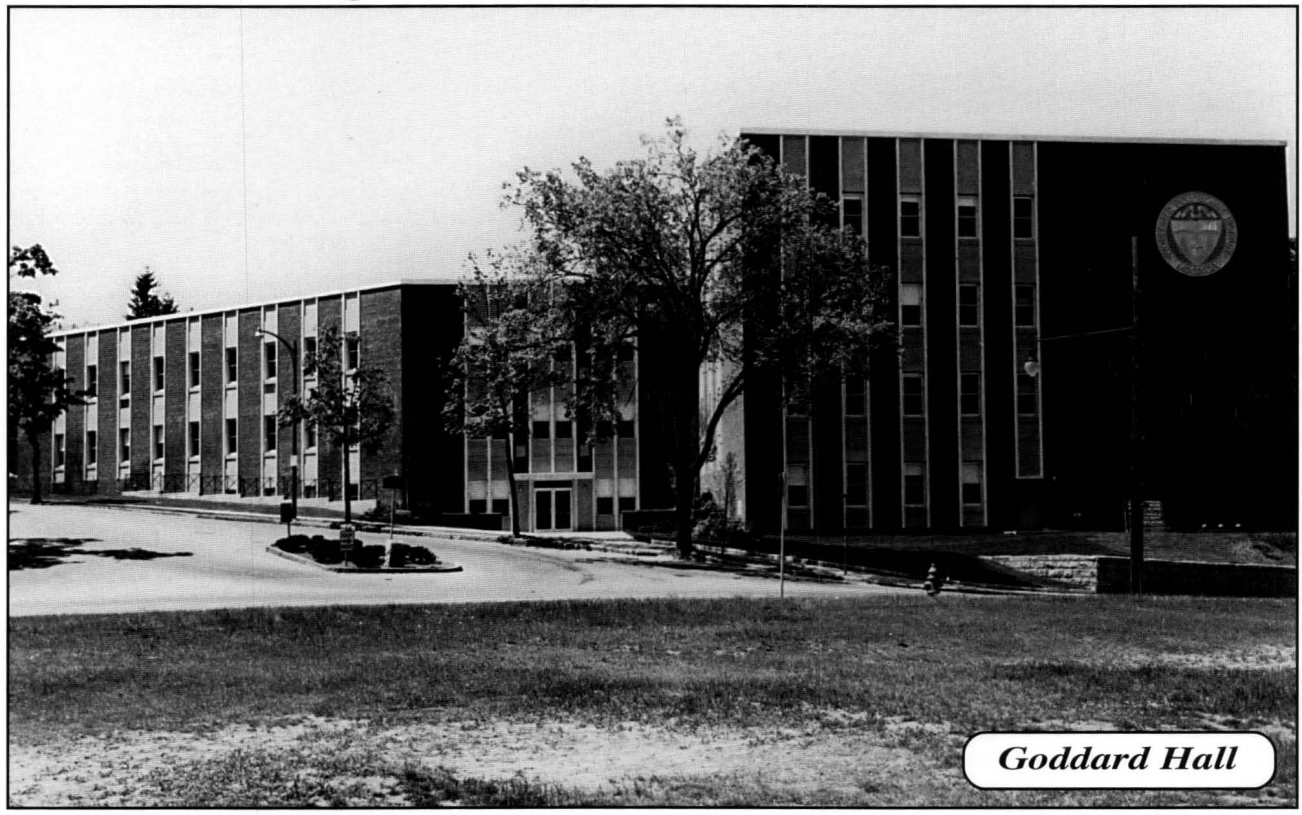
Chemical Engineering at...



Worcester Polytechnic Institute

ALVIN H. WEISS
Worcester Polytechnic Institute • Worcester, MA 01609

Worcester (pronounced "Wustah"), Massachusetts, is situated on seven of the gently rolling hills of the Massachusetts Piedmont. It is about forty-five miles due west of Boston, all uphill. It is considered to be in the Great Midwest, far too distant for most proper Bostonians to venture, except on those weekends when many pass it by on their way to the West (*i.e.,* the Berkshires). When a Bostonian is asked, "What is the best route to San Francisco?" the invariable answer is "Through Worcester."

Given this perception, which has always been the situation, Worcester has developed very independently from Boston. There is surprisingly little interaction, *e.g.,* between WPI and MIT or Harvard.

In addition to WPI, Worcester boasts of having the University of Massachusetts Medical School, Clark University, College of the Holy Cross, Assumption College, Anna Maria College, Becker Junior College, Worcester State College, and Quinsigamond Community College. In short, education is the major industry in this city of less than two hundred thousand. Worcester has a sizeable BioTechnology Park and was home to the Worcester Foundation for Experimental Biology (where the "Pill" was invented). These, together with the research proceeding at the medical school and the other colleges, combine to make Worcester's bio research a major industry. There are also major computer companies in Worcester and the nearby areas (*e.g.,* DEC, EMC, Allegro), as well as a myriad of smaller high-tech companies whose manpower needs draw on the local colleges and universities.

The Blackstone River Valley, in and around Worcester, is considered to be the birthplace of the Industrial Revolution. Worcester still has some of the heavy industry it was once known for, including abrasives (Norton) and heavy forgings (Wyman-Gordon). But much of this low-tech industry has moved away, mainly to the South. At one time there were major wire mills (including US Steel), textile operations, and plastic processors.

Worcester's isolation from Boston has resulted in cultural facilities that developed far beyond the level one might expect for the city's size. These include both the spectacular Worcester Art Museum and Mechanic's Hall (opened in 1857), one of the most acoustically perfect and beautiful concert halls in the nation (the name reflects Worcester's industrial beginnings). The theatre and music seasons provide the best of internationally and nationally known performers and orchestras for concerts, recitals, operas, and theatre. Worcester is quite culturally independent of Boston.

"Students must be taught not only how to create technology, but also to assess and manage the social and human consequences of that technology." That approach is known as "The WPI Plan."

1865—WPI IS FOUNDED

Going back in time to the nineteenth century, it was well-recognized that local industry needed a local source of trained engineers to work in the burgeoning light and heavy manufacturing industry that was successfully operating in Worcester. A local philanthropist, John Boynton, established an endowment of one hundred thousand dollars on May 1, 1865, to establish "The Worcester Free Institute." Thus was established the third oldest technological college in the USA (following RPI and MIT).

"The aim of this school shall ever be the instruction of youth (*boys* of Worcester County) in those branches of education best adapted to train the young for practical life; and especially that such as are intending to be mechanics, or manufacturers, or farmers, may attain the principles of science applicable to their pursuits."

Mr. Boynton's gift was quickly supplemented by a gift of one hundred and ten thousand dollars by Stephen Salisbury of Worcester. The new Institution was chartered by the legislature of Massachusetts and opened to receive its first students on May 12, 1868, as the "Free Institute of Industrial Science of Worcester, Massachusetts." Farmers seem to have been neglected in the list of courses offered: Mechanical Engineering, Civil Engineering and Topography, Architecture, Drawing and Design, Chemistry, and English, French, and German.

The first catalog stated that "Certain [of the above] studies are common to all of these Departments, for it is the aim of the school to give as complete a general education as possible, and to point out the true relation of theory and practice." This statement is, in effect, from the very beginning, the essence of the WPI education. The motto of WPI —Lehr und Kunst (Science and Technology)—states the school's intent to provide engineers and chemists to industry who have not only practical capabilities but also an understanding of the fundamental principles they will need to advance knowledge. It is noteworthy that such a philosophy was new to technical education, which heretofore had been almost universally theoretical and which left the new graduate short on practical skills. To accomplish these goals, the first catalog pointed out the need for practicums. Drafting and design, shop training, and laboratories were required, so that the graduate would be able to enter his profession directly, not as an apprentice who had to learn to apply his theoretical background to practice.

Speeches made at the time (1869) also fixed the goals of the school. Chester S. Lyman of Yale stated, "I see not simply a new institution, but a new class of institutions." Charles O. Thompson, the first Professor of Chemistry and Principal, noted, "It is not the boy we are training, but the giant he is to become." Mr. Thompson also said at that time, "We cannot receive any women without undertaking to instruct all competent women who apply. This we have not room for now. It is our purpose to throw the school open to youth of both sexes as soon as we can." (This finally happened, but it took one hundred years until the first female student graced the halls of WPI.)

PRACTICAL CHEMISTRY— THE BEGINNING OF CHEMICAL ENGINEERING

There was, of course, no such thing as "Chemical Engineering" in 1868. Industrial chemists and mechanical engineers met industry's needs in the chemical technology area. The founders not only felt that it was important for engineers to have an understanding of chemistry, but also that it was important for chemists to have engineering skills. Besides a spectrum of courses in theoretical and applied chemistry, chemistry majors had extensive laboratories in chemistry, focusing heavily on analysis and physical chemical measurements. But they also took the drafting workshops, machine shops, and metallurgy and forging workshops required of the mechanical engineering students. A new building was

opened in 1887 (Salisbury Laboratories) to house facilities for chemistry that ultimately evolved into elaborate unit operations experimentation. It was purported to provide the chemistry students "with even more air to contaminate."

Proceeding to the catalog of 1898, laboratory and workshop capabilities and facilities had advanced considerably, allowing a philosophy of education in which engineering students produced the parts for, and actually built, complex machines. The next step was for the students to actually produce commercially valuable products, and to understand the costs involved in their manufacture and sale. (The revenues obtained from the sale of student-produced products, such as drafting tables, were applied to the costs of education!)

The Chemistry Department had not only General, Analytical, and Organic laboratories, but also very practical Industrial, Sanitary, and Gas Laboratories. These were complemented by chemistry-major courses in General Chemistry, Qualitative Analysis, Quantitative Analysis, Advanced Inorganic and Theoretical Chemistry, Organic Chemistry, Industrial Chemistry, and Thesis. The Chemistry Department also offered Mineralogy (for all students except electrical engineers), Metallurgy (for all students), Sanitary Chemistry (for chemists and civil engineers), and Gas Analysis (for all students except civil engineers).

Seniors received sixty lectures describing the most important chemical manufacturing processes. Visits were made to manufacturing enterprises, and large equipment for grinding, mixing, pressing, filtering, drying, etc., was studied, both at the company's and in Salisbury's laboratory "for study of chemical processes on a large scale."

The catalog states "The principal work in the laboratory is not the preparation of pure chemicals, but rather, the study of practical methods of working up the waste products of various manufacturing industries, which are in reality the student research projects."

The very practical chemistry degree (without, of course, actually bearing the name "chemical engineering") offered in 1898 corresponded very much to the chemical engineering programs at most schools even sixty years later.

DR. ROBERT H. GODDARD— THE FATHER OF MODERN ROCKETRY

On January 6, 1917, Dr. Robert H. Goddard (WPI class of 1908, and Assistant Professor of Physics at the local Clark College) was provided a $5,000 grant through the Smithsonian Institution to further his pioneering work on rockets. He arranged to work together with WPI staff, and the Magnetic Laboratory at WPI was rewired to enable testing of the devices he had made in Clark's Machine Shop. The military potential of his research was immediately recognized, and by January of 1918, he was also working with funds provided by the US Signal Corps. Because of spy paranoia during World War I, it was necessary to hire watchmen; the staff of the Magnetic Laboratory working on the Testing Project grew to about ten. Shots were heard from the small building for about four months, frightening the neighbors on a regular basis. A good deal of public curiosity resulted, and

▲ ***Dr. Robert Goddard's early experiments on rockets were done during World War I in the WPI Magnetic Laboratory, pictured above, which was isolated from other campus buildings.***

Dr. Robert Goddard is shown at his liquid-fueled rocket-launch site in Auburn, Massachusetts (1926) ►

the Signal Corps decided to move the project to Mount Wilson Observatory shops at Pasadena, California, and subsequently to Aberdeen Proving Ground, Maryland. After the armistice was signed, funding for the Project ended abruptly, but the efforts had produced a prototype of the "bazooka" World War II anti-tank weapon.

Dr. Goddard returned to the Worcester area to forge his place in history. On March 26, 1926, the first flight of a rocket using liquid fuel was recorded as having been made from Aunt Effie's Farm in neighboring Auburn. Testing of larger rockets followed in short order, making the neighbors and fire marshal nervous enough to have Goddard exiled to a far corner of Fort Devens, Massachusetts. By 1930, he was in Roswell, New Mexico, continuing his research.

There is no record of formal close collaboration between Robert Goddard and the WPI Chemistry Department, even though his work on liquid-oxygen-fueled rockets encompassed both chemical and chemical engineering principles, not the least of which were design and construction of pumps and cooling systems. WPI felt that it was important to recognize Dr. Goddard's great contributions by naming a new building after him. A grant from the Olin Foundation funded the construction of this new building for the combined Chemical Engineering and Chemistry Department (united under one Department Head in 1940). The new building, named Goddard Hall of Chemical Engineering and Chemistry, was dedicated in 1965. It replaced the old Salisbury Laboratories building.

CHEMICAL ENGINEERING

WPI's first course in "Chemical Engineering" was offered in the Chemistry Department in 1922.* It was a senior course taught by non-resident lecturer Barnett F. Dodge. In 1928, Thomas K. Sherwood was appointed as Assistant Professor of Chemical Engineering. He joined MIT three years later. By 1936, chemical engineering was established so firmly that the department changed its name to Chemical Engineering and Chemistry. Internal jousting resulted in splitting the combined department into two separate departments in 1938; the Department of Chemistry and the Department of Chemical Engineering. The departments merged again in 1940—and separated again, to go their separate ways (possibly forever) in 1967.

Once Goddard Hall was opened, the chemical engineering faculty, with Yankee frugality, moved the antique chemical engineering equipment from Salisbury to the state-of-the-art three-story Goddard Hall unit operations laboratory. An equipment grant allowed the department to purchase sophisticated new pilot-scale experimental units to supplement the old. A decision was also made to increase the chemical engineering faculty in the new building by fifty percent. Eventually, the new faculty, not burdened by the nostalgia of the senior faculty, threw out the old equipment.

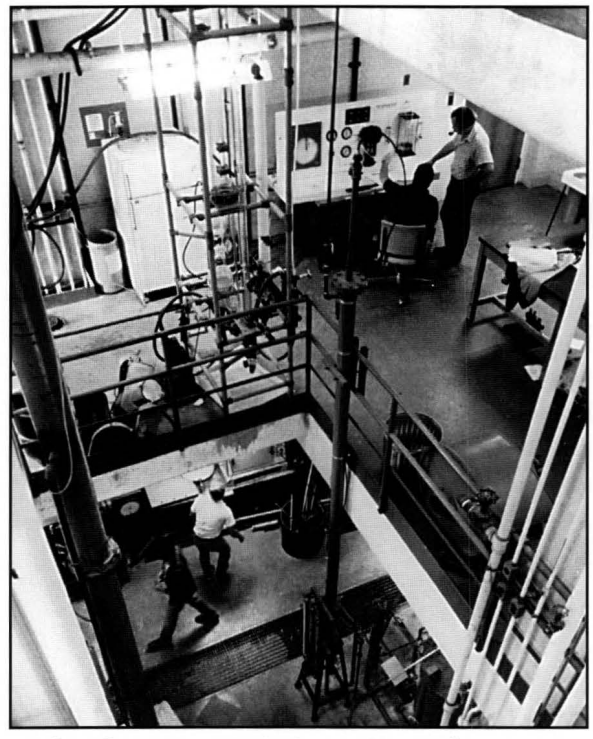
The reason for increasing the size of the chemical engineering faculty was to implement research activities in the department, now that facilities were available. This was quite in accord with new policies that were developing across all of the departments of the Institute. Under the guidance of its gifted Dean of Faculty, M. Lawrence Price, WPI's courses had been completely revised in 1959 to keep up with the new technologies of the era, such as ultrasonics, aerospace, nuclear power, magneto hydrodynamics, cryogenics, etc. The problem became what to stop teaching to make way for the new technologies.

Along with existing technologies, both educational methods and the mechanical equipment in the laboratories were becoming obsolete. Concepts, rather than courses, were now important: *how* to learn, not *what* was learned, was the key point of departure from the past. The need for the type of practical training exemplified by the foundry and manufacturing in Washburn Laboratory had long passed. For example, Washburn was now converted to a 1-KW pool reactor nuclear facility, the only such facility in the Northeast dedicated to teaching (and, of course, research). The Physics Department had installed a Van der Graaf accelerator in its new building for research in nuclear magnetic resonance and X-ray diffraction. WPI's Alden Research Laboratories, located in nearby Holden, had become both nationally and internationally renowned as a center for hydraulic research and development. Forty truckloads of antiquated power equipment were removed from electrical engineering to make way for the new activities in microwaves, electronics, and computers. Civil engineering redirected itself to human problems of environment, safety, health, sanitation, and transportation.

The Chemical Engineering and Chemistry departments shared the new Goddard Hall, and the new facilities allowed research that had been started years before to blossom in both departments. Most notable in chemical engineering were the catalysis research of Professor Wilmer Kranich (the Department Head) and the combustion research of Professor C. William Shipman. Starting in 1965, new faculty were brought in with a departmental goal of establishing a critical research and teaching mass in the related and burgeoning areas of reaction study—catalysis, kinetics, transport, and zeolites. These included, in order of arrival over a three-year period: Imre Zwiebel (adsorption), Alvin Weiss (kinetics and catalysis), Yi Hua Ma (transport and diffusion), Leonard Sand (zeolite synthesis). They quickly aggrandized all available laboratory space and as much funding as could be found, and began to make WPI a well-known name in these areas of chemical engineering research. The Catalysis Society of New England was organized at WPI in 1967, and the Second International Conference on Molecular Sieve Zeo-

** WPI had initiated an advanced one-year professional engineering program in Chemical Engineering in 1917. The first graduate that year was William Bartlett Jones (BS in Chemistry, 1916). The first BS in Chemical Engineering was granted in 1935.*

lites was held at WPI in 1971. The department quickly became recognized as a center for research excellence in the above listed fields, particularly for synthesis of zeolites and for catalytic studies that showed the relationship of acidity to silica-alumina ratio in zeolites. The 1973 energy crisis brought major funding in both energy and environmental areas. Professor Robert Thompson, hired in 1976, became Editor of the *Zeolites Journal* (now *Non Porous and Mesoporous Materials Journal*). International research collaborations on food synthesis in space for NASA established space research as a key activity of the department. Professor Albert Sacco, hired in 1977, became an astronaut and did microgravity zeolite synthesis research during space flight. Professors William Clark and David DiBiasio established biochemical engineering research in the department. Professors Anthony Dixon and William Moser were hired for their respective contributions to transport and catalysis studies.



The Three-story Unit Operations Laboratory has large-sized modern equipment for student experimentation

Endless debates were held in 1968 faculty meetings on the question of admitting female students. There were heated discussions by a small vocal group at these meetings, both about inadequate lavatory facilities for women and about corruption of WPI's young men. Quite unilaterally, the Chemistry Department admitted a nun to the Master's program. The lady had the wit to locate lavatories (and laboratories); and her morals could not be questioned, so the ice was broken. Females now represent about fifty percent of the students in chemical engineering, and three of the current ten chemical engineering professors are women.

THE WPI PLAN—AHEAD OF ITS TIME

An important change in the school's administration took place when Dean Price was joined by the new President of the Institute, Lt. General Harry P. Storke (Ret.). These two men recognized the general state of engineering education at the time. Strict lists of required courses with inflexible prerequisites were the norm in engineering-degree programs across the nation, the goal being the "weeding out" rather than the nurturing of students. But, simultaneously, technology was changing at an unheard-of pace, and there was no way for engineering students to learn everything. What was needed was a new approach to engineering education where the student learned to learn, to acquire skills, and to function, even if he or she faced technologies that were unheard of at the time of their undergraduate education. According to the WPI catalog, "Students must be taught not only how to create technology, but also to assess and manage the social and human consequences of that technology." The approach is known as "The WPI Plan." The first "Plan" students graduated in 1973.

The WPI-Plan undergraduate chemical engineering program now averages fifty graduates per year and is centered on three key projects that distill classroom experience into real-world projects. The vision of the WPI Plan is that the project experiences prepare students to manage team efforts and to communicate exceptionally well, both in oral and written reporting. The Major Qualifying Project is a senior-year chemical engineering study, either laboratory research or a design task (usually as a subset of an ongoing graduate research project). The Interactive Qualifying Project emphasizes the need to understand and to relate how chemical technology affects society and its institutions. There is now a great emphasis on global issues. The project work can be done either at WPI or at any of the seventeen global program sites located both in the United States and in foreign countries. All students also do a project called a "Sufficiency," based on a five-course self-selected coherent series of courses in the Humanities and Arts. The goal is to develop an in-depth understanding and appreciation of one of the cultural aspects of our society.

It seems amazing that this WPI chemical engineering curriculum has existed for three decades. ABET (Accreditation Board for Engineering and Technology) requirements had to shift to accommodate the innovations. The new ABET 2000 requirements actually contain many of the WPI educational elements.

Undergraduates develop their own programs of technical courses (with, of course, careful faculty guidance). There are no prerequisites for any courses. Failed courses disappear from the student's transcript; only successes are recorded. The student can go on to the next course, repeat the course, or forget about it. Apart from their projects, chemical engineering students are expected to complete twelve courses in mathematics and basic science, fifteen engineering science

TABLE 1
Faculty and Their Research

T.A. Camesano
Assistant Professor, PhD, Pennsylvania State University
Bioremediation; bacterial adhesion; atomic force microscopy; colloidal phenomena

W.M. Clark
Associate Professor, PhD, Rice University
Bioseparations; two-phase electrophoresis; aqueous two-phase extraction; membrane filtration; teaching methodologies

R. Datta
Professor and Department Head, PhD, California, Santa Barbara
Catalyst and reaction engineering; supported molten metal catalysts; catalytic microkinetics; fuels and chemicals from renewable resources; fuel cells and reformers; transport in porous media and membranes

D. DiBiasio
Associate Professor, PhD, Purdue University
Bioreactor engineering; magnetic resonance imaging of bioreactors, mammalian cell culture, hollow fiber reactors, immobilized cell reactors; teaching and learning methodologies

A.G. Dixon
Professor, PhD, University of Edinburgh
Reaction engineering; computational fluid dynamics for gas-solid catalytic reactors; dense and porous inorganic membrane reactors; zeolite membrane reactors; heat-transfer problems in fixed-bed membrane and microchannel reactors

Y.H. Ma
Professor, ScD, Massachusetts Institute of Technology
Inorganic membranes; palladium membranes for hydrogen separations; perovskite and perovskite-like membranes for air separation; zeolite membranes, membrane reactors; adsorbent development, adsorption and diffusion

K.M. McNamara
Assistant Professor, PhD, Massachusetts Institute of Technology
Chemical vapor deposition; CVD growth processes for semiconductors; impurity and defect incorporation; optical and electrical properties; materials for space applications; art and historical objects

W.R. Moser
Professor Emeritus, PhD, Massachusetts Institute of Technology

F.H. Ribeiro
Assistant Professor, PhD, Stanford University
Catalysis and surface science; heterogeneous catalysis; kinetics; model catalysts

R.W. Thompson
Professor, PhD, Iowa State University
Applied reactor design and particulate systems; zeolite crystallization; polymer degradation; water purification; film formation

R.E. Wagner
Professor Emeritus, PhD, Princeton University

A.H. Weiss
Professor Emeritus, PhD, University of Pennsylvania

B.E. Wyslouzil
Associate Professor, PhD, California Institute of Technology
Aerosol science; small-angle neutron scattering from aerosols; multicomponent aerosol formation; condensation in supersonic nozzles; aerosol transport in plant tissue reactors

and design courses, and six advanced chemistry courses. The well-rounded graduates of the Plan are qualified and sought after for industrial positions of responsibility, graduate schools, and professional schools. Many WPI graduates occupy key positions throughout the chemical industry.

CURRENT FACULTY AND GRADUATE RESEARCH

The WPI Chemical Engineering Department's graduate program averages about thirty-five graduate students, as well as about ten post-doctoral scientists and visiting professors. The department's ten professors and their fields of research are listed in Table 1. The department plans to grow to a total of thirteen faculty, with increasing emphasis on graduate study and research. Catalysis, zeolites, and reaction engineering continue to be the cornerstones of the department's research recognition, but other active research areas include fuel cells, materials science and technology, environmental studies, life sciences and bioengineering, space sciences and engineering, and computational modeling. The flavor of graduate research is highly international, and papers are presented at conferences throughout the world. Graduate study also involves a great stress on the student's research and great independence in course selection. Almost every project incorporates undergraduate participation, giving the graduate student experience in leadership.

CONCLUSION

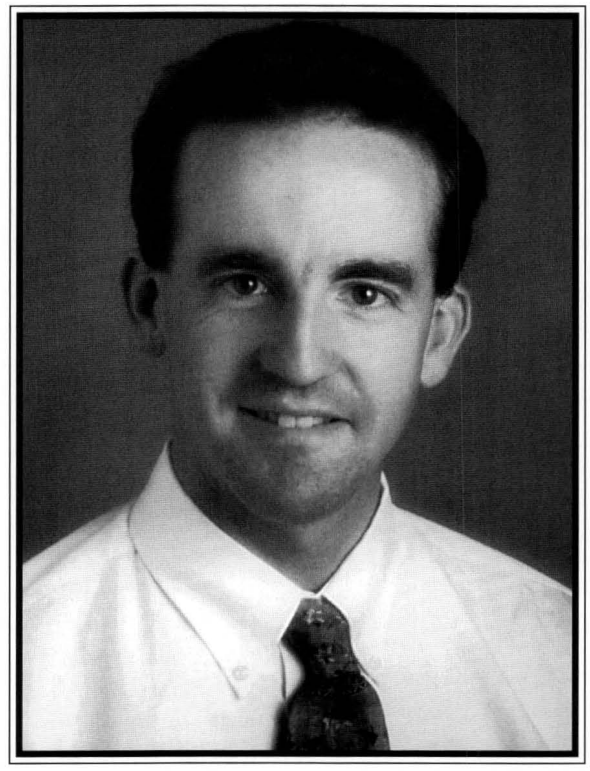
There is no denying the dramatic changes that are occurring in chemical engineering technology. New instrumentation and concepts develop constantly. Most basic chemical and petroleum industry products are now commodities, resulting in limited growth in traditional industries. Although there is much debate on the future of the discipline, WPI's approach to chemical engineering of "Learning to Learn" accommodates present and future contributions of chemical engineers in new, as well as existing, technologies. The independence given the student in structuring his or her own program of courses, in managing and doing teamwork on projects, in oral and written reporting, guarantees future leaders in our discipline. The substantial exposure to humanities, other cultures, and international activities and commerce, produces well-rounded chemical engineers ready to function in today's world. Many schools have followed or are considering anew WPI's example in chemical engineering education. It is a future path of education for the discipline.

ACKNOWLEDGMENTS

The author wishes to express his thanks for the help given by Laura Brueck, Archivist of WPI's Goddard Library, in providing background information for this article. Considerable historical information has also been taken from the book *Two Towers* by Mildred McClary Tymeson (Library of Congress Catalog Card 64-66162). The author appreciates the support and information provided by Professor Ravindra Datta. ❐

Frank Doyle III

Reflections from his friends and colleagues



Edgar Allan Poe is rumored to have placed a curse on the city of Newark, Delaware, after a bad experience in a local watering hole. The curse: "Anyone who is in Newark cannot wait to leave, and when you are gone, you are homesick for Newark." This legend has special significance for Frank Doyle, who grew up in Newark, left for college and graduate school, and after sixteen years has returned to teach at the University of Delaware.

The origins of Frank's interest in chemical engineering can be traced to Newark. First, his father is a chemical engineer (he is the Information Technology Manager at the nearby Motiva Refinery), which seems to have influenced both Frank and his younger brother Patrick. Second, he was drawn to chemistry and mathematics from as early in his education as the eighth grade. He recalls attending classes on Saturday mornings to learn algebra under the watchful eye of Sister Mary Alice. Frank recalls, "The nuns at my high school almost talked me out of chemical engineering—however, the alternative they had in mind was the priesthood."

Although Frank grew up in the shadow of the top-ranked chemical engineering program at the University of Delaware, he chose to go out of state to Princeton University for his undergraduate training. His decision was partly based on the proximity of his parents' house to the campus, and partly on his desire to pursue a well-rounded Ivy League education. In fact, English was his second choice for a major.

To balance the challenging workload at Princeton, Frank became involved in the varsity sailing team and served as its co-captain in both his junior and senior years. A love of sailing was also a result of his father's influence; his father had built his own sailboat when Frank was only five. In his senior year, Frank was awarded the "Class of 1916 Cup" for the varsity athlete graduating with the highest GPA.

On the academic front, the biggest influence on Frank while at Princeton was Roy Jackson, with whom he worked on his senior thesis. Frank's thesis won the Xerox Prize for the most outstanding thesis in the chemical engineering department. Professor Jackson's command of the English language and his ability to communicate ideas in the classroom greatly influenced Frank's decision to pursue an academic career, and it set a standard for Frank in effective classroom teaching. Roy was also a role model as a mentor, and he taught Frank the valuable lesson of impartial advising.

In 1985, as graduation neared, Frank kept all his post-graduate options open as he applied for business school,

. . . he was drawn to chemistry and mathematics from as early in his education as the eighth grade. . . "The nuns at my high school almost talked me out of chemical engineering—however, the alternative they had in mind was the priesthood."

engineering graduate school (chemical and nuclear), industrial positions, and study-abroad programs. "It's good to have options," he observes. He also weighed a decision to join the nuclear navy when he was a junior at Princeton. He soon realized, however, that submarines were a poor approximation for sailing on the surface, and he quickly came to his senses and decided to go to graduate school instead.

In the end, Frank was drawn to the field of process control as his graduate research topic. There were a number of events that steered Frank toward the field of dynamics and control. They included summer internships in 1981 and 1982 with a process control instrumentation company (Process Control Inc.), as well as a senior-year course in process dynamics and control.

After talking to Professor Jackson about his experiences as a student at Princeton, Frank decided to spend a year at Cambridge University and was awarded a Winston Churchill Fellowship in 1985. He worked with professor Allan Hayhurst on the development of an ionization sensor for a spark ignition engine. This thesis project was in some ways a prelude to his PhD work as his project involved a novel sensor for a feedback loop in an engine control system.

In Frank's effort to immerse himself in the local British lifestyle, he took up rowing, cricket, and pub hopping. His rowing activities eventually led to participation on the chemical engineering boat to race in the Cambridge town bumps. His team went on to "bump" each of the four nights of the regatta, and each member was awarded his own oar as a trophy. That oar is Frank's prized souvenir from his Cambridge days. At the end of his year there, Frank was awarded the W. Averell Harriman Scholar prize for being "the most outstanding Churchill Scholar" in the program in 1986.

Leaving the dreary weather of England for sunny California, in the fall of 1986 Frank began work on his PhD at the California Institute of Technology. He chose that program because of its intimate class size and because of the international reputation of Manfred Morari's research program in process control there. Morari taught Frank about the importance of close interaction with students as well as how to think critically. Frank practices what he learned with his own research group by having weekly one-on-one meetings and weekly student seminars, and by setting a high standard for the group.

In spite of the grueling schedule of graduate school, Frank found time to keep his love of sailboat racing alive. He was fortunate enough to become part of a three-person team and qualified for the World Championship in the Echells class while at CalTech.

But, sailing had an even more important consequence in Frank's life—he met his future wife, Diana, during a regatta weekend in Newport Beach.

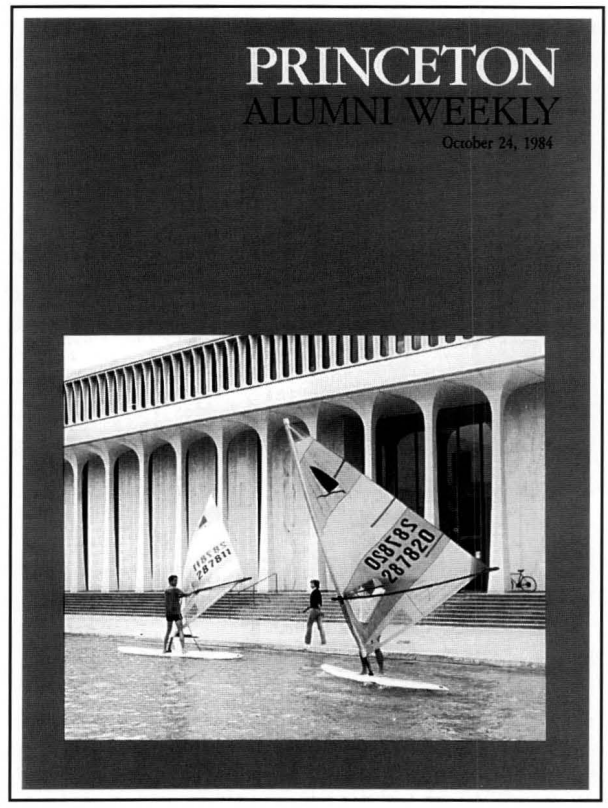
Members of the Churchill College rowing Team at Cambridge University competing in a regatta on the river Cam in the fall of 1985. Frank is rowing in the stroke position facing the coxswain.

TEACHING AND RESEARCH

In 1991, as Frank was putting the finishing touches on his PhD, he accepted an offer to teach at Purdue University. Recognizing the practical nature of Purdue's program, however, he felt he would be a better teacher if he had some industrial experience under his belt before standing in the front of a classroom. A chance meeting with W. David Smith at the CPC IV meeting led to working for DuPont in 1991, prior to commencing his career at Purdue. Dr. Tunde Ogunnaike, a collaborator from the group, recalls:

My first professional contact with Frank began as a result of a program instituted in 1990 at DuPont. In an attempt to promote more meaningful interaction between academia and industry, with the objective of encouraging research efforts focused on problems of industrial significance, our group at DuPont instituted an academic visiting-scientist program. The first ever "Young Faculty" visiting position was offered to Frank. By the end of his year in this program, Frank had established what would become the gold standard by which all subsequent program participants would be measured. I had the privilege of working very closely with Frank during this one-year period; it was to be the beginning of a long and fruitful collaboration that continues to this day.

Nearly ten years after, it is now possible to see the importance of Frank's year at DuPont in shaping his career; from his teaching style and his selection of research problems to the formation and operation of the University of Delaware Process Monitoring and Control Consortium. Each activity bears the unique trademark of strong theoretical and analytical fundamentals appropriately tempered with practical considerations. Frank has also evolved into one of only a few academicians who are well-regarded both in industrial as well as academic circles; in Frank's case, he is not only a productive researcher, he is also an all-around good citizen of the chemical engineering community at large.



***Princeton Sailing Team Co-Captains, Frank Doyle and Rob Schoelkopf pull a stunt with windsurfers in the Woodrow Wilson Plaza pool that landed them on a 1984 cover of* Princeton Alumni Weekly.**

While at DuPont, Frank learned about practical problems and the challenges in implementing control in the real world. He collaborated with Tunde and Ron Pearson on Volterra series model-based control; they have continued those interactions through the years and are presently writing a book on the subject. Frank also kindled an interest in biosystems control through a collaborative project with Tunde and Jim Schwaber, and that collaboration has likewise been maintained through the years despite several employment changes by both Jim and Frank. They studied the way that nature regulates blood pressure on a beat-by-beat basis; that project led to a major thrust of biosystems analysis and control in Frank's research—several years before the DuPont Life Science revolution took place.

In the fall of 1992, Frank headed to Purdue to start teaching and building his own research group. His research program took root quickly, and he was awarded the National Science Foundation's National Young Investigator Award for his process control work in 1992. This was followed in 1996 by the Office of Naval Research Young Investigator Award for his research on biosystems analysis and control.

Purdue introduced a new teaching challenge for Frank—a large classroom environment. But, he took it as an opportunity to establish his lectures with multifaceted ways of interacting with his students through a combination of lectures, labs, help sessions, and office hours. He organized a tutorial session in the evenings with the dual purpose of going over some complex problems that would capture the attention of the accelerated students and solving them in complete detail for the benefit of students who need a little extra help.

Frank was greatly influenced in his teaching style by Phillip Wankat, who taught a course at Purdue on teaching engineering. In that class, Frank first learned about the "learning types" that helped him in approaching diversity in the class-

room. His hard work and dedication paid off. Frank was awarded many teaching awards in the next few years, including ASEE Section Outstanding Teacher Award (Illinois/Indiana, 1996); Shreve Prize, Chemical Engineering Department teaching award, 1995, 1997; A.A. Potter Award, School of Engineering teaching award, 1995; Purdue's Teacher's for Tomorrow Award, 1996; and Tau Beta Pi's Dean Marion B. Scott Exemplary Character Award, 1996. In 1996 he was also inducted as a member of the first group of elite teaching faculty in the Teachers-for-Tomorrow program.

Frank also began development of a set of educational software modules while at Purdue. With the encouragement of his departmental head, Rex Reklaitis, he created a virtual laboratory for process control—constrained by the large class sizes at Purdue (as high as 200 graduating seniors). After a number of years of hard work by his graduate and undergraduate students, the modules were published as a book in 1999 by Prentice Hall, under the title of *Process Control Modules—A Software Laboratory for Process Control.*

In addition, Frank established a significant program on both traditional process control and in the area of biosystems control that he had studied at DuPont. The traditional process control research was expanded by interactions with the other process systems engineering faculty at Purdue (Reklaitis, Pekny, Venkatasubramanian). The four faculty co-founded the very successful Computer Integratred Process Operations Center (CIPAC). One of the themes that was championed by Frank was the application of advanced systems engineering methods to the pulp and paper industry. He would later place two of his Purdue PhD students at top pulp and paper companies, and has established himself as a leading researcher in that industry. Dr. Philip Wisnewski, one of Frank's first PhD students (presently at Weyerhaeuser) recalls:

> *Frank has influenced me, as he has many of his students, by the example of professionalism that he exudes. He sets very high standards for himself; and through his dedication to teaching and research; through his sincerity, honesty, and loyalty in dealing with others; and through his support and encouragement which he freely offers to his students, he inspires those around him to set high standards and expectations for themselves. Frank is truly a gentleman, a person of quality and integrity.*

Frank also expanded his biosystems research activities to include biomedical-engineering control problems and began a collaboration with Nicholas Peppas in 1994 with two jointly advised graduate students in the area of controlled drug delivery for diabetic patients. One of those students, Robert Parker, is now an Assistant Professor in the Chemical Engineering Department at the University of Pittsburgh. Professor Peppas offers these words to describe his colleague:

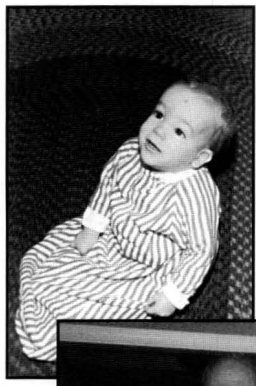
> *Frank is a truly unique individual, an outstanding researcher, and a most gifted teacher and educator. He brings a great deal of creativity and ingenuity to the classroom. By bringing his real chemical engineering experiences to the students, instead of just textbook examples, he not only helps them to learn but also to want to learn even more. For Frank, teaching is not a job, but a mission.....Our research interaction over the past six years has taught me that he is one of the most imaginative and innovative chemical engineers of our times. He has an uncanny ability to grasp difficult biomedical ideas and transfer them to the level of systems theory.*

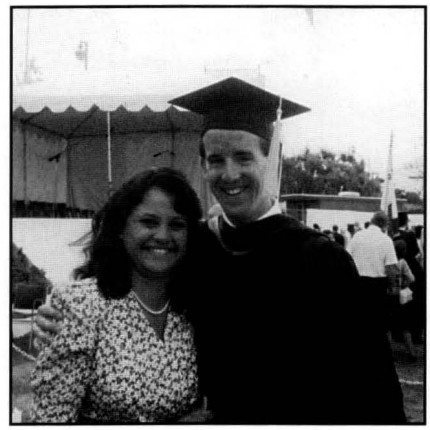
On a personal note, although Frank was far from the coast while he was a Purdue, he still sailed as often as he could on Lake Michigan, often accompanied by his wife Diana and his daughters Sara and Brianna.

" . . . he is not only a productive researcher, but he is also an all-around good citizen of the chemical engineering community at large."

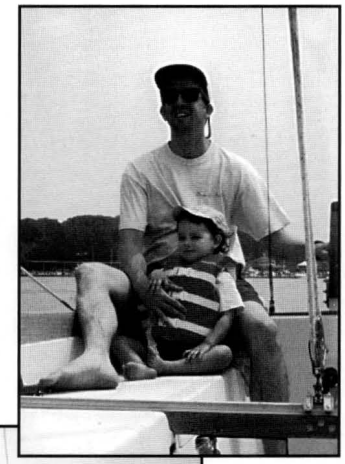
Family Album

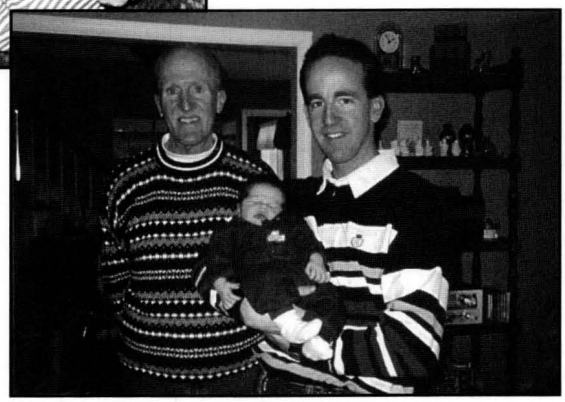
Frank, at one year of age (top) and all grown up, the centerpiece of three generations of Doyles (bottom). ▽





◀ Frank and his future wife Diana at his PhD graduation at CalTech in June of 1991.





Frank has introduced his daughters to his favorite hobby—sailing. Here with two-and-a-half year old daughter Sara (top) and one-year-old Brianna (bottom) aboard their sailboat "Son of a Sailor" in 1998.

DELAWARE DAYS

In 1997, Frank took advantage of an opportunity to move closer to home; he accepted a faculty position at the University of Delaware. It was a rare opportunity to advance both his professional and personal pursuits. Here, Frank continues to make a major impact on innovation in teaching. In the spring of 1998, he was one of several instructors to beta-test a new program for a web-based class organizer called SERF (Server-side Educational Records Facilitator). SERF allows students to view curriculum, homework questions, send e-mail to the class and to the professor, check on their progress in the course, and review lecture notes. Frank has published conference papers and a book chapter about his experiences using SERF for control education. He was also inducted as a Fellow in the NSF-sponsored Institute for Transforming Undergraduate Education at the University of Delaware.

Frank was also the first instructor at Delaware to employ live video streaming via the Worldwide Web in his fall 1998 control class. He worked with the staff of Media Services to create an on-line version of his course to facilitate the schedules of students who were on industrial internships as well as to engage a more geographically distributed continuing education audience. The experience formed the basis of an invited book chapter on the subject. A student taking the class off-site said

> *It has given me the knowledge and insight into the subject that would have taken me several years to acquire on my own. Prof. Doyle was very receptive to student questions both in and out of class and was very professional.*

As mentioned earlier, Frank has also developed an interactive software package for undergraduate dynamics and control education known as PCM (Process Control Modules). The modules were published in the fall of 1999 as a textbook with the CD-ROM. The software is developed in the MATLAB and Simulink environment and incorporates several realistic simulation models of industrial unit operations (furnace, distillation column, bioreactor, pulp digester, chemi-

cal plant). The accompanying exercises demonstrate dynamic analysis, PID controller design, frequency response analysis, and controller tuning. There are numerous chemical engineering departments in the world using this software for process control education.

Another of Frank's teaching innovations at the University of Delaware was the development of a college-wide interdisciplinary, experimental control-engineering course. The course is centered around a state-of-the-art laboratory developed using actual industrial control equipment and software from Aspen Technology, ABB/Bailey, and Honeywell. The experiments include a distillation column, a gyroscope, an inverted pendulum, a servomotor, a level control system, and a spring-mass damper. The course has drawn students from chemical, electrical, and mechanical engineering as well as from operations research, which is outside the college.

Frank's educational activities were recognized in 2000 by the Ray Fahien Award from the Chemical Engineering Division of the ASEE. He is also serving on the Provost's Teaching and Learning Technology Roundtable, which has a mission to define the university's vision for effective teaching technology tools.

The work of Frank's research group at Delaware is characterized by two dominant themes: 1) the application of nonlinear model-based control techniques to multivariable, nonlinear, constrained industrial processes, and 2) the use of systems-analysis tools as a bridge between chemical engineering and biology through neuromimetic and therapeutic approaches. At Delaware, Frank has also taken on a new research challenge—an experimental project. His group built a pilot-scale emulsion polymerization reactor shortly after their arrival that is interfaced to state-of-the-art industry sensors and control hardware. With an objective of particle size distribution control, it will serve as a test bed for a number of control projects in his research program. Frank feels there is no simulation substitute for the complex nonlinear behavior that his research team will face in trying to optimize the operation of this system.

The practical impact of Frank's research is also evidenced by establishment of the University of Delaware Process Control and Monitoring Consortium in 1998, shortly after his arrival. Frank is the director of this Consortium that has the support of twelve industrial companies and involves collaborations across campus, including chemical engineering, mechanical engineering, computer science, and computer engineering. The Consortium structure enables participation of both industrial companies and control vendors with the university in the pursuit of applied research.

SERVICE

Frank maintains a healthy perspective about service work in the academic profession: "...it is the responsibility of the most active members of the teaching and research community to take a leadership position in service activities." As such, he has served on a number of important committees, including the graduating recruiting activities at both Purdue and Delaware. He has served on many search committees, including three concurrently in early 2000. He holds two editorial posts with the *Journal of Process Control* (Special Papers Editor) and *IEEE Transaction on Control Systems Technology* (Associate Editor). He has organized or chaired over thirty sessions at meetings of the AIChE or ACC and is on the International Programming Committee of many of the conferences in the process control area. His teaching service has led him to give lectures to high school teachers on technology topics as well as to the members of the Academy for LifeLong Learning (a continuing education group for retirees) on diabetes therapy research.

Although Frank is a young faculty member, he has already had a large influence on the students in the profession. He estimates that approximately 900 seniors have taken his process control course, and of those, approximately 40 have done independent research projects under his supervision. He is presently advising, or has supervised, over 20 MS and PhD students in his relatively short career.

PERSONAL LIFE

Frank was born in Philadelphia in 1963, but moved to Newark, Delaware, at the age of 2. He was the oldest of five children and has three sisters and a brother (Patrick—also a chemical engineer). Frank married his wife Diana in 1992 and they have three beautiful children: Sara (age 4), Brianna (age 3), and newborn Francis Joseph IVth. Now that Frank is "back home" in Delaware, he enjoys sailing the Chesapeake with his parents and hopes to introduce his children to the excitement of sailboat racing. Another perk of returning home is the renewal of hope for ending a 25-year losing streak on the tennis court to his father. He is involved with the Knights of Columbus in the Parish where he went to grammar school.

THE FUTURE

Frank sees many changes ahead for the field of chemical engineering, both in teaching and research. There is no question in his mind that future research successes will occur at the boundaries between disciplines, and he feels confident that biosystems and chemical engineering will be a fruitful path. On the educational front, he sees similar challenges as the new ABET requirements put an increased emphasis on interdisciplinary coursework. He is presently working with his Dean and the department heads in the college to create a common control engineering course for all the engineering majors. He also has plans to tap the power of the World Wide Web to create tools for process control education. ❐

THE FUTURE OF ENGINEERING EDUCATION

Part 5. Assessing Teaching Effectiveness and Educational Scholarship

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Armando Rugarcia • *Iberoamericana University* • *Puebla, Mexico*
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The first four papers in this series[1-4] offered a number of ideas for effective teaching and preparing faculty members to teach. An inevitable question is, how does one determine whether or not a faculty member's teaching is effective? Another important question is, how does one determine whether or not an instructional *program*—such as that of an engineering department—is effective?

The instructional component of the mission of every educational institution is to produce graduates with satisfactory levels of knowledge, skills, and attitudes.[1] The specific knowledge, skills, and attitudes may differ from one department to another and the definition of satisfactory may differ from one institution to another, but the instructional mission is invariant. In engineering, the basis of a department's accreditation is the extent to which the department is fulfilling this mission. An instructor may be a brilliant lecturer with student ratings at the top of the charts, but if his or her teaching is not furthering the instructional mission of the department, that teaching cannot be considered effective.

To appraise programmatic teaching effectiveness, we must answer the following questions:[5,6]

1. ***Educational goals***. *What are the published goals of the instructional program? Does the faculty know what they are? Does the faculty generally agree with them?*
2. ***Performance criteria***. *Are the criteria that will be used to evaluate faculty performance measurable and clearly tied to the goals? Does the faculty know what they are? Does the faculty generally agree with them?*
3. ***Assessment process***. *What assessment data will be collected? How and when and by whom will they be collected and analyzed? Are available resources (including faculty time) adequate to permit their collection and analysis?*
4. ***Evaluation process***. *How will conclusions about teaching effectiveness be inferred from the data, and by whom? What type of feedback will be provided to the faculty, and when and by whom will it be provided?*

The answers to these questions should be based on the university mission statement and program accreditation requirements, with additional criteria and procedures contributed by the program administration and faculty.

An additional factor enters into the appraisal of an individual faculty member's teaching performance—namely, the extent to which he or she is contributing to the improvement of education. We refer to this performance factor as *educational scholarship*. It encompasses developing or systematically improving teaching methods and methods of assessing learning outcomes, writing textbooks and courseware, and publishing scholarly papers and monographs and giving work-

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Armando Rugarcia *graduated from the Universidad Iberoamericana (UIA) in 1970 and went on to earn his MS in chemical engineering from the University of Wisconsin in 1973 and his Doctorate in Education from West Virginia University in 1985. He has been a full-time professor of engineering at UIA since 1974 and was Chair of the Chemical Engineering Department there from 1975 to 1980. He was also Director of the Center for Teaching Effectiveness at UIA from 1980 until 1986. He has written four books on education, one on process engineering, and more than 130 articles.*
James Stice *is Bob R. Dorsey Professor of Engineering (Emeritus) at the University of Texas at Austin. He received his BS degree from the University of Arkansas and his MS and PhD degrees from Illinois Institute of Technology, all in chemical engineering. He has taught chemical engineering for 44 years at the University of Arkansas, Illinois Tech, the University of Texas, and the University of Wyoming. At UT he was Director of the Bureau of Engineering Teaching Center and initiated the campus-wide Center for Teaching Effectiveness, which he directed for 16 years.*

shops and seminars on education-related topics. For individual faculty performance evaluation (as opposed to instructional program evaluation), the questions listed above should therefore be augmented by these:

5. ***Educational scholarship***. *What evidence of scholarly contributions to education will be collected? How and by whom will the evidence be evaluated?*

In this paper we suggest options for answering most of these questions. We first propose principles of instructional assessment and summarize common violations of these principles. Then we elaborate on how to assess the effectiveness of both teaching and educational scholarship, leaving the evaluation process (determining what qualifies as satisfactory performance) to be determined by institutional norms and values.

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SEMANTIC NOTES

In the educational literature, the two terms *assessment* and *evaluation* are constantly encountered. They are sometimes used interchangeably as synonyms for appraisal of instructional effectiveness; sometimes assessment denotes the appraisal of individual teaching and evaluation the appraisal of teaching programs;[5,6] and sometimes assessment denotes collecting and analyzing data that reflect on teaching quality and evaluation denotes interpreting the assessment outcomes and drawing conclusions about teaching quality.[7] Unless otherwise noted, we will use the latter definitions in our discussions.

An important distinction is that between *formative assessment,* which has improvement of teaching as its objective, and *summative assessment*, which produces information that can be used to make decisions about instructional personnel or programs. Formative assessment is (or should be) an important part of institutional programs to help faculty members become more effective as teachers, a topic discussed in the preceding paper in this series.[4] This paper concerns summative assessment.

CRITERIA FOR EFFECTIVE COURSE INSTRUCTION

Evaluation of either programmatic teaching effectiveness or individual faculty member performance involves assessing the quality of instruction in individual courses. Extensive research supports the use of the following criteria as a basis for the assessment:[8-15]

1. The course contributes toward published program goals.
2. The course has clearly stated measurable learning objectives.[2]
3. The assignments and tests are tied to the learning objectives and are fair, valid, and reliable.[2]
4. Appropriate methods have been devised to monitor the effectiveness of the instruction.
5. The learning environment is appropriate.[2,3]
6. The instructor has appropriate expertise in the course subject.
7. The instructor communicates high expectations of students and a belief that they can meet those expectations, interacts extensively with them inside and outside class, conveys a strong desire for them to learn and motivates them to do so.
8. The instructor seeks to provide an education in the broadest sense of the word, not just knowledge of technical content.[1]
9. The instructor integrates teaching with research.
10. The instructor continually attempts to improve the course by updating the content and/or making use of new instructional materials and methods (including applications of instructional technology).
11. The students achieve the learning objectives.

More details are given by Woods.[15]

ASSESSMENT AND EVALUATION OF TEACHING EFFECTIVENESS

An assessment plan should involve assembling several types of evidence to determine the degree to which the foregoing criteria are being met. Among the possibilities are the following:

- *Learning outcomes assessments: student performance on standardized tests, comparisons of student performance with performance of control groups, evaluations of student products by external reviewers.*
- *Student end-of-course ratings.*
- *Student surveys, focus groups, or interviews directed at specified criteria.*
- *Retrospective student ratings of courses and instructors (e.g., pre-graduation ratings by seniors).*
- *Alumni ratings of courses and instructors.*
- *Peer ratings of classroom instruction, learning objectives, assignments and tests.*
- *Evaluations submitted by external referees.*
- *Self-evaluations by instructors.*

The assessment data may be collected for individual faculty members in *teaching portfolios* (or *teaching dossiers*), which may be evaluated by a review team to provide an effective assessment of instructional effectiveness. The portfolios assembled by all members of a department collectively provide a partial basis for evaluating the effectiveness of the department's instructional program. More would have to be done to demonstrate that the program graduates meet specified criteria related to their knowledge, skills, and attitudes (such as those specified as Outcomes 3a–3k of ABET Engineering Criteria 2000).

Assessment of Learning

The ultimate assessment of teaching is assessment of learning. Teaching that does not satisfy institutional, departmental, and individual instructors' learning objectives cannot be considered effective, regardless of what other assessment measures may indicate.

The past decade has seen a growing realization that the traditional assessment tool used in undergraduate engineering education for most of the past century—the written examination on material covered in lectures and readings—provides an inadequate measure of the knowledge, skills, and attitudes that engineering schools wish to impart to their students. Driven in large part by the impending adoption of Engineering Criteria 2000 as the accreditation system for all U.S. engineering departments, a large and constantly growing body of work on the systematic assessment of specified learning outcomes has arisen. A full review of this literature is well beyond the scope of this paper; what follows is a brief summary of the principal ideas.

Assessment—whether of learning or teaching, whether for individual courses or entire instructional programs—can only be done meaningfully in the light of clearly stated goals and measurable objectives. In the case of assessment of learning, the requirements are explicit statements of the knowledge, skills, and attitudes that the students are supposed to acquire (the goals) and of what the students must do to demonstrate that the goals have been met (the objectives). The following assessment tools may be used as part of that demonstration. The terms in parentheses indicate the categories of objectives that the specified tools may be used to assess, including outcomes specified by Engineering Criteria 2000.

❑ **Complete tests and individual test items** (*knowledge, conceptual understanding, engineering problem-solving skills*). Tests given in engineering courses may provide good measures of relative learning among students in a particular class, but they are frequently unsuitable for assessment of true conceptual understanding and problem-solving skills. They may also provide misleading results. For example, if tests are too long for most students to finish (a situation that unfortunately characterizes many engineering tests), students who work sloppily but quickly may earn much higher grades than students who work accurately but slowly. The most meaningful assessment is provided when the test results may be compared with established norms or with results from comparison groups, such as another class taught in parallel to the one in question by a different instructor and/or using a different instructional method. The nationally normed Fundamentals of Engineering (FE) examination has the potential to provide a basis for assessment.[16]

❑ **Laboratory reports, design project reports, live or videotaped oral presentations, research proposals** (*knowledge, conceptual understanding, analysis, creative thinking, critical thinking, experimental design, identification of engineering problems, teamwork, written and oral communication skills, professional or social awareness, lifelong learning skills*). The usual drawback of reports as assessment instruments is subjectivity in their evaluation. One way to improve their effectiveness is to use detailed checklists in evaluating the reports, tying the checklist items to specific learning objectives. Even greater assessment validity is provided by using several independent raters who reconcile their ratings after completing their checklists.

❑ **Resumes, letters, memos** (*written communication skills, professional or ethical awareness*). An effective way to prepare students to function as professionals is to ask them to engage in common professional activities and provide them with feedback on their efforts. For example, periodically ask engineering students to prepare resumes and to write letters and memos dealing with common hypothetical

situations, such as reporting a result to a supervisor, asking for an interview with a prospective employer, persuading a client or a prospective client to purchase a product or service, or recommending an action to a superior or a subordinate in a situation that has ethical implications.

❑ **Critiques of technical reports, papers, letters, and memos** (*analysis, critical thinking, written communication skills*). It is often easier to see weaknesses in someone else's work than in one's own. Having students critique one another's first drafts of written documents and revise their own documents based on the feedback they get helps them develop critical thinking skills, especially if the critiques are collected and graded. The papers handed in to the instructor are generally much better than they would have been without the preliminary feedback, and the grading job of the instructor is consequently much less burdensome.

❑ **Self-evaluations, learning logs, journals** (*any skills or attitudes*). Surveying or interviewing students is a direct way to obtain their impressions of how much their skills have improved as a consequence of their education. The validity of such data is greatest if the data are consistent with results obtained by other means, or if the same data are available for comparison groups subjected to different forms of instruction. Student learning logs or journals can be rich indicators of the degree of acquisition of selected skills and attitudes, but trained evaluators are needed to make such inferences and the process can be extremely time- and labor-intensive.

❑ **Other classroom assessment techniques** (*any skills or attitudes*). The classic reference on classroom research by Angelo and Cross[17] suggests a large variety of techniques for assessing knowledge, recall, understanding, and ability to apply learned information; skills in analysis and critical thinking, synthesis and creative thinking, and problem solving; and self-awareness as learners. While the usual applications of these techniques are formative, any of them may also be used for summative assessment.

A comprehensive picture of student learning is provided by assembling *student portfolios*—longitudinal records of student learning assessment results. Panitz[18] describes uses of portfolios for both formative and summative purposes at different schools. Some instructors allow students to determine how much weight should be assigned to different course components, assemble the portfolios themselves, indicate the grade they think they have earned, and write a statement indicating how the portfolio contents justify the grade. Others set up competency matrices of one type or another. One format consists of rows for different student products in the portfolio and columns for specific learning outcomes or objectives, with marks to show which products demonstrate which outcomes or the levels (A, B, C,...) at which the objectives are satisfied. Rogers and Williams[19] describe a web-based portfolio system created at the Rose-Hulman Institute of Technology. Students enter work that they believe demonstrates their progress toward meeting specific performance criteria and state justifications for their claims, and faculty raters evaluate the entries.

Student Ratings of Instruction

The most common method—and in many programs, the only method—of assessing instructional quality is to collect student ratings at the end of each course. The rating form is often haphazardly designed, and the results may be difficult to interpret with any degree of objectivity. In part because of these defects, many faculty members discount the validity and value of student ratings. Commonly heard criticisms are that ratings do not correlate with quality of learning and the easiest teachers get the highest ratings.

In fact, more than a thousand research studies of student ratings have been performed, and the results collectively show that ratings are reliable, stable over time, and positively correlated with results obtained using other forms of teaching assessment, including assessment of learning outcomes.[20-23] Contrary to popular assertions, they are not affected appreciably by the instructor's personality or gender or the time of day a class is offered.[21] Difficult courses that do not require unreasonable expenditures of time and effort are rated somewhat more favorably than courses that lack challenge.[22] Some studies show positive correlations between ratings and grades, but it is not clear whether the higher grades in the more highly rated courses reflect inappropriately easy grading or superior learning. The positive correlations observed between ratings and learning outcomes suggest that the latter may be a strong contributing factor.

Their validity notwithstanding, student ratings should not be the only method used to assess instructional quality. There are several important aspects of teaching that students lack the knowledge and perspective to judge fairly, including the currency and importance of the course content, the instructor's understanding of the subject, and the appropriateness of the assignments, tests, and grading policies.[22-24] Many institutions use non-standardized assessment instruments and fail to take into account extraneous factors such as class size, course level, and whether courses are required or elective, making the results for different faculty members difficult or impossible to compare.

Nevertheless, course-end student ratings are an essential component of instructional quality assessment. As long as they are to be collected, certain steps should be taken to maximize their effectiveness.[25]

❑ **Collect ratings of the effectiveness of the course and the instructor in a few critical aspects.** The most commonly used format is probably the five-point Likert scale (e.g., 1=strongly disagree, 2=disagree, 3=neutral, 4=agree,

5=strongly agree) applied to items related to the quality of teaching and learning in the course. The following items have been shown to be related to teacher effectiveness as measured by mean student performance on examinations:[26]

- *Each class period was carefully planned in advance.*
- *The instructor presented the material clearly.*
- *The professor made students feel free to ask questions, disagree, express their ideas, etc.*
- *The professor used examples from his/her own research or experience.*
- *This course has increased my knowledge and competence.*

Other questions might be asked related to acquisition of specific skills included in the course goals (*e.g.,* critical or creative thinking, writing, teamwork, etc.). Since a standardized form is desirable for summative assessment, however, the items chosen should be small in number and general enough to apply to different courses and instructors within a single discipline and across disciplines. (For formative assessment, items may be included on any aspect of the instruction on which the instructor wishes feedback.) The form should not contain questions about things the students are not equipped to evaluate, such as the instructor's knowledge of the subject.

❑ **Collect overall course-end ratings of instruction**. "Rate the instruction you received in this course on a scale from 1 to 5, with 1 being the highest response." Ratings of this sort are most effective when the numbers on the response scale are clearly defined. Definitions like "excellent," "above average," "fair," etc., are subjective and ambiguous, and when they are used a very broad performance range tends to be lumped into "above average." Greater discrimination is obtained by giving descriptions of the characteristics of instructors in each category, making it clear that very few instructors are likely to fall into the extreme categories.

One approach is to use a norm-referenced system, wherein 5 means that the instructor is one of the three best teachers the student has ever had (or is in the top 1% or the top 5%), 1 signifies one of the three worst teachers (or the bottom 1% or 5%), and 2, 3, and 4 represent different percentile ranges (*e.g.,* bottom 20%, middle 60%, and top 20%). The problem with this system is that it penalizes faculty members in departments with a large number of excellent instructors. A better approach calls on students to base their overall rating on the average of their ratings of individual characteristics of the course and instructor (previous bullet). For example, the students could be asked to total their ratings of the individual items, and ranges for the total could be given on the form that translate to overall ratings of 5, 4, 3, 2, and 1. The ranges corresponding to the highest and lowest overall ratings should be relatively narrow (*e.g.,* a total that would yield an average rating in the range 4.75 to 5.0 might correspond to an overall rating of 5; 3.75 - 4.75 to a rating of 4; 2.25 - 3.75 to a 3; 1.25 - 2.25 to a 2; and 1 - 1.25 to a 1). If this system were used, instructors who get 5 would clearly be worthy of nomination for an outstanding teacher award and instructors who get 1 would clearly have very serious problems with their teaching.

❑ **Administer and collect course-end ratings in a single class session rather than counting on students to return them later**. Results of evaluations for which the return rate is less than a minimal percentage should be regarded with deep suspicion: the recommended minimum is 50% (classes of 100 or more), 66% (50-100), 75% (20-50), and 80% (<20).[27] The environment used for gathering the data should include student anonymity and absence of the instructor from the room.

❑ **Interpret ratings collected over a period of at least two years**. One semester of low ratings (or high ratings, for that matter) does not provide a valid measure of an instructor's teaching effectiveness.

❑ **Periodically collect retrospective student evaluations in addition to course-end ratings.** Ratings from seniors and alumni of how well individual instructors helped them acquire knowledge and develop skills are powerful indicators of teaching effectiveness. These retrospective ratings help identify the relatively small percentage of instructors whose students only appreciate their effectiveness as teachers years after taking their courses. For faculty members at research universities, ratings from former research advisees attesting to the degree to which professors promoted their intellectual curiosity and research skills should also be sought.

Peer Ratings

Peer ratings can contribute significantly to the evaluation of teaching if they are well designed and conducted, but the common practice of having untrained faculty members sit in on a lecture and make notes on whatever happens to catch their attention yields results that are neither reliable nor valid.[28] To be effective, summative peer ratings should include the features described below.[29,30]

❑ **Who should do the reviewing?** Reviewers should be good teachers who have received training on what to look for in a classroom and who recognize that different styles of teaching can be equally effective. Training dramatically increases the likelihood that evaluations from different reviewers will be consistent with one another (reliability) and with accepted standards for good teaching (validity).

❑ **How should classroom observations be performed?** At least two reviewers should conduct at least two class visits during a semester, preceding each visit with a brief meeting at which the instructor provides information about the class to be observed. The reviewers independently complete stan-

dardized rating checklists after each observation and soon afterwards visit with the instructor to discuss their observations and invite responses. After all individual observations and reviews have been completed, the reviewers compare and reconcile their checklists to the greatest extent possible and write a summary report to be placed in the instructor's teaching portfolio or personnel file.

❑ **What should the lecture observation checklist contain?** The checklist is a collection of statements about the observed classroom instruction with which the reviewers indicate their levels of agreement or disagreement, adding explanatory comments where appropriate. Statements such as the following might be included:[31]

- **Organization**. The instructor (a) begins class on time, (b) reviews prior material, (c) previews the lecture content, (d) presents material in a logical sequence, (e) summarizes main points at the end of the period, (f) ends class on time.
- **Knowledge**. The instructor (a) has a good understanding of the course material, (b) integrates ideas from current research and engineering practice into the lectures, (c) answers questions clearly and accurately.
- **Presentation**. The instructor (a) speaks clearly, (b) holds the students' attention throughout the period, (c) highlights important points, (d) presents appropriate examples, (e) encourages questions, (f) seeks active student involvement beyond simple questioning, (g) *attains* active student involvement, (h) explains assignments clearly and thoroughly.
- **Rapport**. The instructor (a) listens carefully to student comments, questions, and answers and responds constructively, (b) checks periodically for students' understanding, (c) treats all students in a courteous and equitable manner.

Many other statements could be included, some of which might be particularly applicable to laboratory or clinic settings. Examples of validated observation instruments are given in a recent book edited by Seldin.[31]

❑ **How should instructional materials be rated?** Examination of instructional objectives, lecture notes, assignments, tests, and representative student products may provide a better picture of teaching effectiveness than classroom observation. Trained observers can judge whether (a) the objectives cover a suitable range of knowledge and skills, (b) the course content is sufficiently comprehensive and current, (c) the assignments and tests are appropriately rigorous, fair, and consistent with the stated objectives. As with classroom observation, the ratings should be done by two or more independent observers using a validated checklist and reconciled to arrive at a consensus rating.

The Teaching Portfolio

The *teaching portfolio* (or *teaching dossier*) is a device used for assessing the teaching effectiveness of an individual faculty member, as opposed to effectiveness of instruction in a single course or of an instructional program. The portfolio is a summary of teaching assessment data, including self-assessment. Most authors who discuss portfolios[32-38] do so in the context of formative assessment and recommend customizing the portfolio to fit the strengths and objectives of the individual faculty member. In keeping with the theme of this paper, we will confine our discussion to summative assessment, which requires using a standard format to provide evaluative consistency.

A recommended format for a summative portfolio consists of several parts:

❑ **Preamble**. Context of the portfolio, time period covered, and outline of the contents.

❑ **Reflective statement of teaching philosophy, goals, and practices**. The instructor's answers to such questions as: "What is my mission as a teacher?" "What skills and attitudes should I be helping my students develop?" "What methods am I using in and out of class to fulfill my mission and enable my students to develop the desired skills and attitudes?" "What am I doing to motivate and equip them to succeed, academically, professionally, and personally?"

❑ **Summary of teaching and advising responsibilities**. Titles, levels, contact hours, and class sizes for all courses taught over the past five years, annotated with brief comments about the way each course is taught. Number of students advised and comments about the nature of the advising. Comments should relate explicitly to the reflective statement and to published institutional and departmental goals.

❑ **Representative instructional materials and student products.** Illustrative assignment statements and tests with grade distributions. Copies of outstanding and typical graded assignments, tests, and project reports. Discussion of the materials in the context of the reflective statement.

❑ **Evidence of teaching effectiveness**. Results of student ratings in the context of average departmental ratings for the same courses over the past six years. Results of retrospective senior and alumni ratings and peer ratings. Results of learning assessments, including student performance on standardized tests. Data from instruments that assess approaches to and attitudes toward learning such as the Lancaster Approaches to Studying Questionnaire and the Course Perceptions Questionnaire[3,15,39] and the Perry or King/Kitchener Inventory.[3,6,15] Reference letters from students and alumni. Implications of the evidence in the context of the reflective statement.

❑ **Efforts to improve teaching effectiveness**. Steps taken to keep knowledge of course content and effective instructional methods up-to-date: workshops, seminars, and conferences attended, papers read, networking done. Steps taken to obtain student feedback and to monitor and improve the

learning environment and quality of classroom instruction.

❑ **Teaching innovations**. New courses developed and changes made to existing courses. New instructional materials generated, teaching strategies adopted, and methods used to motivate and empower students. Copies of publications or presentation abstracts describing innovations. Discussion of the innovations in the context of the reflective statement.

❑ **Evidence of effectiveness of advising and mentoring**. Successes of and recognition received by advisees. Reference letters from advisees. Implications of the evidence in the context of the reflective statement.

❑ **Awards and recognition**. Nominations for awards and awards received (include award criteria). Other recognition.

When the portfolio is used as part of the basis for personnel decisions (e.g. awarding of promotion or tenure or determining merit raises), it should be independently reviewed by at least two raters who have been trained in portfolio evaluation. Following a predetermined scheme, the raters should assign values to the quality of reflection and documentation, the instructor's commitment to high quality teaching and learning, and the instructor's teaching and advising effectiveness and (if appropriate) educational scholarship. The raters should compare and discuss their ratings, make any changes they believe to be appropriate, and arrive at a consensus rating. The individual and consensus ratings should be included in the portfolio to be used in the decision-making process.

Eventually, the department head must make a determination of teaching effectiveness based on his or her review of the assessment data. A form for guiding this review is available from the Kansas State University IDEA Center.[24]

ASSESSMENT AND EVALUATION OF EDUCATIONAL SCHOLARSHIP

In his landmark work *Scholarship Reconsidered*,[40] Ernest Boyer proposed that academics can pursue scholarly activities in four different arenas: *discovery* (advancement of the frontier of knowledge in a discipline), *integration* (making connections across disciplines, putting research discoveries in broader contexts and larger intellectual patterns), *application* (applying the outcomes of discovery and integration to socially consequential problems), and *teaching* (helping students acquire knowledge and develop skills). Boyer argued that these four areas are all equally vital to the mission of the research university and that universities should therefore recognize and reward them all equally.

The publication of *Scholarship Reconsidered* intensified an ongoing discussion about the role of teaching in the evaluation of faculty performance at research universities. Among the focal questions of the discussion are "What is educational scholarship?" and "How can you assess its quality?" The following discussion is taken largely from a recent article that addresses these questions.[41]

What is educational scholarship?

Boyer lists the elements that make teaching a scholarly activity:[40]

1. **Subject knowledge**. The scholarly instructor has a deep conceptual understanding and a broad awareness of the current state of knowledge of the subject being taught.
2. **Pedagogical knowledge**. The scholarly instructor can formulate analogies, metaphors, and images that build bridges between his or her understanding of the subject and the knowledge and level of experience of the students. The instructor is also familiar with a variety of effective instructional methods and the research base that confirms their effectiveness.
3. **Commitment to continuing growth as an educator**. The scholarly instructor is committed to continuous improvement of his or her disciplinary and pedagogical knowledge. Indications of such a commitment are books read, journals subscribed to, and seminars, workshops, and conferences attended.

A fourth element might be added to this list:[41]

4. **Involvement in development, assessment, and dissemination of innovative instructional methods and materials**.

Instructors who keep their subject knowledge current, learn about and implement effective teaching methods, and continue to work on improving their teaching may be said to be effective teachers, worthy of being nominated for whatever rewards the institution offers for teaching effectiveness, but they are not necessarily educational scholars. To qualify for that title, we propose that they must also undertake the activities associated with traditional disciplinary research: innovation and rigorous assessment and evaluation of the innovations. In educational scholarship as in disciplinary scholarship, the fruits of the labor might be products (e.g., textbooks or instructional software) or processes (e.g., new or improved methods for motivating students, promoting their intellectual development, or assessing their learning). Also as in disciplinary scholarship, making results available to the professional community for evaluation, replication, and adoption is a necessary component of educational scholarship.

The improving climate for educational scholarship

In the past, even if engineering professors were inclined to do scholarly work in education there were barriers to their doing so successfully. Grants for engineering education research were in short supply and provided minimal funding. Engineering education journals did not require rigorous assessment as a condition for publication, and journals in

education and educational psychology that did so were not receptive to contributions of an applied nature from other disciplines. Engineering administrators and faculty peers called on to evaluate faculty performance reports were unfamiliar with the education literature and generally discounted all education-related papers, including those that adhered to good assessment practices and were published in journals with high standards. Campus awards for outstanding scholarship in teaching did not exist.

The climate for scholarship in engineering education has become considerably warmer in recent years. The National Science Foundation has provided millions of dollars of funding through its Division of Undergraduate Education and the Engineering Education Coalition program, and corporate foundations have also provided significant support to efforts to improve engineering education. The *Journal of Engineering Education* has become a first-rate vehicle for scholarly publications, and other high-quality refereed journals now accept papers on engineering education research.[15] National, regional, and—on some campuses—local awards for outstanding scholarship in engineering education are given. Unfortunately, many who rate faculty performance in engineering are still inclined to discount education-related activities as not worthy of being counted toward promotion, tenure, and merit raises, funded and published though they may be. Hopefully, this situation will also improve before too long as more and more professors are motivated to undertake serious efforts to study and improve engineering education—rigorously setting goals, developing measurable outcomes, gathering data about the effectiveness of their interventions in the classroom, and subjecting the data to rigorous analysis and interpretation.

How can educational scholarship be assessed and evaluated?

Earlier in this paper, we proposed that for teaching to qualify as a scholarly activity, the instructor should demonstrate a command of both subject and pedagogical knowledge, a commitment to continuing growth as an educator, and an involvement in innovation in teaching and dissemination of results. We further propose that assessment of an instructor's educational scholarship should consist of answering the following three questions:[41]

1. *Did the teaching qualify as a scholarly activity?*
2. *Was the teaching effective?*
3. *Were the innovative products and processes developed by the instructor well conceived, implemented, assessed and evaluated, and disseminated?*

The data obtained using the assessment tools described in the preceding sections of this paper and summarized in the section on the teaching portfolio should be adequate to assess the first two questions. To answer the third question, the same forms of evidence traditionally used in the assessment of disciplinary research may be gathered. Acceptable evidence includes the number and quality of conference presentations, invited seminars, books, monographs, and refereed publications; number of grants and contracts; citations of publications; referee comments on submitted manuscripts and grant proposals; internal and external reference letters and comments, and recognition and awards.

The following standards proposed by Glassick, *et al.*,[42] provide a good basis for evaluating the quality of educational innovations:

1. ***Clear goals***. *Is the basis of the work clearly stated, the questions addressed important in the field, and the objectives realistic and achievable?*
2. ***Adequate preparation***. *Does the scholar show an understanding of existing scholarship in the field, the necessary skills to do the work, and the ability to assemble the necessary resources?*
3. ***Appropriate methods***. *Were the methods used appropriate to the goals, applied effectively, and appropriately modified when necessary?*
4. ***Significant results***. *Were the goals achieved? Did the work contribute significantly to the field? Did it open areas for further exploration?*
5. ***Effective presentation***. *Was the work presented effectively and with integrity in appropriate forums?*
6. ***Reflective critique***. *Does the scholar critically evaluate his or her own work, bringing an appropriate breadth of evidence to the critique and using the critique to improve the quality of future work?*

Faculty members who meet these standards are clearly vital to both the educational and scholarly missions of the university. They merit advancement up the faculty ladder—tenure, promotion, and merit raises—no less than faculty members who meet institutional standards for disciplinary research.

SUMMARY

The assessment of teaching should done for a clearly defined purpose—to evaluate teaching effectiveness (summative assessment) or to improve it (formative assessment). It should be done in the context of published goals, measurable performance criteria, and agreed-upon forms of evidence. The evidence should come from a variety of sources, including learning outcomes assessments, student end-of-course ratings, student surveys, focus groups, or interviews, retrospective student evaluations of courses and instructors, alumni and peer evaluations, and self-assessments.

The ultimate measure of the effectiveness of teaching is

the quality of the resulting learning. As with any other area of assessment, meaningful assessment of learning requires prior formulation of learning goals and measurable objectives that address all desired knowledge, skills, and attitudes. Tools for assessing learning include tests and test items, written reports and proposals, oral presentations and interviews, student-generated critiques of work produced by others, student self-evaluations, learning logs and journals. The validity of inferences drawn from the data is increased if norms or control group responses are available for objective tests and test items and if multiple independent evaluations are submitted and reconciled for subjective judgments such as ratings of written project reports and oral presentations.

Student ratings of teaching are a valid and important source of evidence for teaching effectiveness, especially if they are averaged over at least a two-year period. Extensive research shows that student ratings correlate positively with both learning outcomes and ratings submitted by alumni and peers. They should not be the sole instrument used to evaluate teaching, however, since students are generally not qualified to judge aspects of instruction like the currency and importance of the course content, the depth of the instructor's knowledge, and the appropriateness of the assignments, tests, and grading policies. Peer ratings are the most appropriate source of such judgments.

The common approach to peer rating is for untrained faculty members to observe lectures and write about whatever catches their attention, an approach that yields information of doubtful value. For peer ratings of instruction in a course to be reliable and valid, the ratings should be obtained from at least two good teachers who have received training on what to look for in a classroom. The raters should use a checklist of items regarding specific aspects of the instruction and associated instructional materials (syllabi, handouts, assignments, and tests), and the independent ratings should be reconciled to arrive at a consensus rating.

A summative teaching portfolio may be assembled to evaluate the teaching effectiveness of an individual faculty member (as opposed to the effectiveness of teaching in a single course or an instructional program). The portfolio should contain a reflective statement of the faculty member's teaching and advising philosophy, goals, and practices; a summary of teaching and advising responsibilities; representative instructional materials and student products; assessment data that reflect on teaching and advising effectiveness; documentation of efforts to improve effectiveness; a summary of teaching innovations (new courses, instructional materials, and teaching methods developed, and education-related papers and presentations); and a list of teaching awards and award nominations. When the portfolio is used as part of the basis for personnel decisions, at least two independent evaluations of the portfolio should be performed by trained raters and reconciled.

Since the publication of *Scholarship Reconsidered*,[40] recognition has been growing that teaching can be a scholarly activity no less than disciplinary research, and that scholarship in teaching should play the same role in determining faculty advancement that disciplinary research has played for the past four decades. Following Boyer, we propose that the defining elements of scholarly teaching are mastery of subject knowledge, familiarity with both general and subject-specific pedagogy, and commitment to continuing personal growth as an educator, and we propose the additional element of involvement in development, assessment, and dissemination of innovative instructional materials and methods. The innovations should reflect an awareness of the current state of the art of engineering education, and analysis and evaluation of the results should adhere to the same standards of rigor customarily applied to traditional disciplinary research.

Assessment of the quality of a faculty member's educational scholarship should be based on the answers to three questions: (1) Did the faculty member's teaching qualify as a scholarly activity? (2) Was his/her teaching effective? (3) Were his/her innovations well conceived, implemented, assessed and evaluated, and disseminated? The faculty member's subject knowledge, pedagogical knowledge, commitment to continuing personal growth, and involvement in innovation (the elements of scholarly teaching) and the effectiveness of the teaching can be judged from the material assembled in a teaching portfolio. The quality and impact of educational innovations can be inferred from the same forms of evidence used to evaluate disciplinary research (number and quality of books, papers, and presentations; literature citations; number of research grants and contracts; reference letters; and recognition and awards). Faculty members who meet or exceed institutional standards for educational research merit the same recognition and opportunities for advancement as faculty members who excel in disciplinary research.

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THE FUTURE OF ENGINEERING EDUCATION

Part 6. Making Reform Happen

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We have dealt in this series with changing conditions in technology and society that will require major reforms in engineering education,[1] instructional techniques that have been shown by theoretical and empirical research to produce learning outcomes consistent with these reforms,[2,3] ways to prepare faculty members to implement the techniques,[4] and effective techniques for assessing both teaching and educational scholarship.[5]

Those were the easy matters. The real challenge is to create a favorable climate for these changes at research universities—a climate that motivates faculty members to improve their teaching and the quality of instruction in their departments, supports their efforts to do so, and rewards their successes. In this paper we suggest steps that might be taken to create such a climate.

THE FALL AND RISE OF TEACHING AT RESEARCH UNIVERSITIES

Evidence of the low status of undergraduate education at research universities for the past half century is easy to find. Every campus has its stories of outstanding teachers being denied tenure because their record of research funding and publications was judged inadequate. Tenured professors commonly warn their non-tenured junior colleagues not to spend too much time on their teaching, telling them that a teaching award before tenure is the "kiss of death."

Growing numbers of administrators and faculty members acknowledge that a problem exists. Gray, *et al.*,[6] surveyed over 23,000 academics in 47 United States universities and concluded that many faculty, chairs, deans and academic administrators at research universities believe that an appropriate balance between research and undergraduate teaching does not now exist at their institutions. Knapper and Rogers[7] report a similar result of a recent extended survey that included Canadian faculty and administrators.

Faculty members of the eight campuses comprising the SUCCEED Engineering Education Coalition were recently asked to rate the importance of teaching effectiveness to them, to their colleagues and administrators, and in their institution's faculty reward system, with 0 being not at all important and 10 being extremely important.[8] On average, the 504 respondents rated the importance of teaching to them personally at 9.3, the importance to their colleagues and administrators in the range 7.0–7.3, and the importance in the faculty reward system at 4.7. In the respondents' open comments about administrative support for teaching, the term "lip service" came up with remarkable frequency.

The teaching and assessment methods described in the first five papers can be used by any instructor at any institu-

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tion, but while most of them do not require a heavy allocation of resources, they all require time and effort to learn, implement, and refine. As long as faculty members feel that their efforts to improve teaching will be largely unappreciated and unrewarded—and in fact could jeopardize their chances for advancement up the faculty ladder—educational reform will be difficult to achieve. In such a climate, the temptation is great to simply dust off and recycle the old lecture notes once more.

On the brighter side, a positive shift in campus attitudes toward teaching began in the early 1980s and has grown steadily since then. There were several catalysts for this shift, including reports by the National Research Council, the National Academy of Engineering, and the American Society for Engineering Education that called for reforms in engineering education.[9] Another driver for change was a growing chorus of complaints from employers of engineers about deficiencies among recent graduates in the skills needed for success in modern engineering practice.[9,10] Responding to these calls, the National Science Foundation began to provide significant funding for education-related research and to consider the impact of proposed research on education in its proposal review process, and ABET adopted the outcome-based Engineering Criteria 2000 as its accreditation standard beginning in 2001.[11] Administrators and faculty members are beginning to recognize that new instructional methods and materials will be required to receive continued accreditation if that standard is rigorously enforced.

Evidence for the growing importance of effective undergraduate instruction at research universities is abundant. Presentations at ASEE conferences and submissions to the *Journal of Engineering Education* have grown dramatically in both number and quality. Tested innovations in teaching methods, technology-based instruction and distance education, assessment and evaluation of teaching and learning, design across the curriculum, and multidisciplinary curriculum integration are described with increasing frequency in the literature.[12] Teaching seminars and workshops are regularly presented to engineering faculty and graduate students on campuses where nothing of the sort had ever been done. In its annual offerings from 1991 through 1999, the National Effective Teaching Institute has reached 472 professors of engineering and engineering technology from 157 institutions, many of whom have gone back to present programs on their home campuses. These are indeed exciting times for engineering education.

It is not yet time to break out the champagne, however. The dramatic progress made in recent years notwithstanding, most engineering classes still consist of professors talking and writing on the board and students sitting and listening (or not listening); rigorous assessment of learning and teaching is still not part of the culture of most institutions; faculty members are still not routinely given any preparation for teaching; and senior faculty are still advising junior faculty (often correctly) that if they spend too much time on their teaching they could be jeopardizing their future academic careers.

As long as faculty members feel that their efforts to improve teaching will be largely unappreciated and unrewarded—and in fact could jeopardize their chances for advancement up the faculty ladder—educational reform will be difficult to achieve. In such a climate, the temptation is great to just dust off the old notes and teach the way they were taught.

Most faculty members are reluctant to move away from the familiar and comfortable teaching methods with which they were taught, especially if they believe that changing methods will require substantial expenditures of time and could hinder their chances for tenure and promotion. They will only consider doing so if they are first made aware of the need for change, presented with alternative methods, given convincing evidence of the effectiveness of the alternatives, and assured that adopting the methods does not necessarily require sacrificing syllabus coverage or spending less time on research.

A prerequisite for significant educational reform is therefore the establishment of instructional development programs that provide this information and these assurances. Another necessary condition for reform is for faculty members to be convinced that their efforts to improve teaching will not work against their career advancement, and that if successful, the efforts can in fact work in their favor.

Descriptions of the need for change, alternative teaching methods, and evidence of the effectiveness of those methods are given in the first five papers in this series. The next section suggests how faculty members can make meaningful improvements in teaching without spending excessive

amounts of time or shortening their syllabi, and how they can deal effectively with student resistance to student-centered teaching methods. The section after that proposes tangible steps that administrators might take to make their campus culture supportive of educational reform.

RESPONSES TO FACULTY CONCERNS ABOUT ALTERNATIVE TEACHING METHODS

Finding Time to Plan and Implement Changes

...they are advised to select only one or two ideas at a time and try them long enough for the students to acclimate to the new methods.

In their teaching workshops, the authors caution the participants that if they try to implement every new technique they hear about, they will probably be overwhelmed by the time they find themselves spending and the student resistance they encounter, get discouraged, and go back to old ways of doing things.

Instead, they are advised to select only one or two ideas at a time and try them long enough for the students to acclimate to the new methods. If a method seems to be working well, they should keep on using it; if it seems to be ineffective, they should first check back in the literature to make sure that the recommended guidelines have been followed, and if they have, discontinue it. Some time later (perhaps in the following semester or quarter), they might try another one or two new ideas. There is no hurry.

Many effective instructional strategies take relatively little time to plan and implement, several of which are listed below. Instructors who have been teaching traditionally and wish to make changes might consider trying one or two of these strategies first, consulting earlier papers in the series for details.

- Motivate the presentation of each new topic by relating it to previously learned material and familiar applications, perhaps starting with a realistic problem or illustrative case study.
- Write clear instructional objectives for course topics and give them to the students as study guides for tests.
- Assign brief small-group activities in class (have the students respond to questions, formulate questions, begin problem solutions, carry out steps in problem solutions and derivations, brainstorm ideas,...)
- Have students complete one or two out-of-class assignments in teams (rather than moving immediately to full-scale formal cooperative learning).
- Periodically ask students to monitor and reflect on their learning, either in the form of minute papers (What was the main point of the lecture? The muddiest point?) or using feedback forms collected at the end of a lecture period. The instructor need only skim the responses to look for patterns and begin the next class by responding to common points of confusion; it is not necessary to provide individual feedback on every response.
- Collect midterm evaluations of the class. (What am I doing in this class that is helping you learn and you would like me to continue to do? What am I doing that is hindering your learning and you would like me to discontinue?) Respond to any reasonable suggestions made by more than two students, accepting those you wish to accept and explaining why you will not go along with the others.

Once comfortable with these strategies, instructors should gradually move on to methods that involve greater departures from usual teaching practice and take more time to implement.[2,3]

Covering the Syllabus

...the goal of teaching is not to cover material but to uncover it. Virtually all cognitive scientists agree that people learn by doing and reflecting not by watching and listening...

At teaching workshops that advocate active and cooperative learning and other student-centered instructional methods, the first question is almost invariably a version of "Can I do all that without sacrificing coverage of important course content?"

Our initial response to this question is that the goal of teaching is not to cover material but to *un*cover it. Virtually all cognitive scientists agree that people learn by doing and reflecting, not by watching and listening to someone else tell them what they are supposed to know.[13]

Instructors can present almost any amount of material in any amount of time by using transparencies or presentation graphics and

talking quickly enough, but there is not much point in doing so if hardly any of the material is being learned.

Having said that, we add that using active learning does not require reducing the syllabus. It is true that in-class activities take time (although not nearly as much as instructors who have not used them fear), and if these activities are included in classes and no compensatory changes are made, content coverage might indeed decrease.

Compensatory changes *can* be made, however. Felder and Brent[13] propose that instructors take large chunks of the lecture material they usually present explicitly in class—the complete step-by-step derivations, sentences, flowcharts, schematics, and plots—and give them to the students in handouts or a coursepack. The handouts should include gaps—missing steps in derivations, axes with no curves shown, questions and problems with spaces for answers to be filled in.

The students can skim through short sections of the notes during class, and the instructor can either lecture on the gaps, get the students to work in small groups during class to fill them in, or leave the gaps to be filled in outside class. The instructor should caution the students that he/she will put variants of the gaps on the tests and then do it.

If this recommendation is followed, most students will read the notes and make sure the gaps get filled one way or another—at least after the first test, when they discover that the instructor was serious about including them.

Class sessions can now be devoted primarily to the most important and/or conceptually difficult material in the lecture notes, and the students will have opportunities during those sessions for the action and reflection that lead to true learning. The class time the instructor saves by not having to spell out every word and formula in the lecture notes is sufficient to allow for all the active learning exercises he/she might wish to include, and the syllabus may actually be expanded to cover *more* material rather than less.

Defusing Student Resistance

Students do not always welcome unfamiliar teaching methods with open arms, especially if the new methods push them out of the comfort zone in which the instructor tells them everything they need to know and then asks them to repeat it on the test. Students introduced to active learning, for example, sometimes accuse their instructors of not doing their jobs when they require the students to learn some things on their own. This hostile reaction is extremely disturbing to instructors who are not expecting it and don't know how to deal with it, and many who encounter it become discouraged and revert to the less effective but safer lecture-based approach.

Students do not always welcome unfamiliar teaching methods with open arms.... This hostile reaction is extremely disturbing to instructors who are not expecting it and don't know how to deal with it,

The occurrence of student resistance is familiar to anyone who has attempted a student-centered instructional approach like cooperative or problem-based learning.[15-18] Woods[15] suggests that students who find themselves deprived of the support they are used to getting from their instructors go through some or all of the stages that psychologists associate with the grieving process: shock, denial, strong emotion, resistance and withdrawal, surrender and acceptance, struggle and exploration, return of confidence, and integration and success. Some students quickly pass through or even skip some of the stages and others get stuck and never emerge from one of them for the entire semester, but the process is a natural one and instructors should not be surprised when they see its sometimes unpleasant manifestations in their students.

Felder and Brent[17] suggest several things instructors might do to hold down the resistance to student-centered instruction long enough for the students to start seeing the benefits of the approach for themselves.

- **Start early, start small, and build.**

  Instructors planning to use a student-centered approach should start using it near the beginning of the course, making their goals and expectations clear from the outset. If they have not used the approach before, however, they should not make it the primary mode of instruction in the course the first time they try it. It is better to take small steps and gradually increase the level of commitment to the approach, never venturing too far beyond the zone of personal comfort and confidence.

- **Explain what you are doing and why.**

  When students are plunged into a new instructional approach—especially one that shifts some of the burden of learning away from the instructor and onto them—they may assume that they are guinea pigs in some sort of experiment and react negatively. Before any of the new methods are implemented, they should be outlined to the class and some of the reasons for using them given, and periodic reminders might be beneficial at several points during the semester. Felder and Brent[17-18] outline several

arguments that can be offered, including research results that demonstrate the learning benefits of the methods and statements about the relevance of the methods to the engineering workplace.

- **Be flexible when implementing new instructional methods.**

  Some students in every class have unique needs and constraints for which allowances should be made. For example, if students are supposed to work in teams outside class on homework assignments or projects and a student has a full-time job or commutes to campus from a considerable distance, he or she might be permitted to work individually. Several students in a class in the same position could be organized into a virtual team that works together on an Internet chat facility or via periodic conference calls. At a commuting campus where many students would find it difficult to meet outside class hours, the instructor might set up a number of virtual teams or make provision for teams to use some class time to work on their projects.

- **When all else fails, consult the manual.**

  If student hostility to an instructional method is excessive or if it seems to be growing rather than diminishing with time, check back in the literature on the method to see if any recommendations (including those just given) have been neglected. If any have, take remedial measures.

CREATING A POSITIVE CAMPUS CLIMATE FOR TEACHING

Excellent teaching has generally enjoyed vigorous rhetorical support from university administrators but limited tangible reward or public recognition. Excellent research, on the other hand, yields summer salaries, funds for national and international travel, release from teaching and service responsibilities, merit raises, and most significantly, tenure and promotion.

The components of academic research—fundraising, planning, carrying out and assessing research projects, supervising graduate students, giving seminars, and writing papers, among other tasks—all take a great deal of time. The components of college teaching—learning and implementing effective teaching and assessment methods, designing and updating courses to reflect the current state of the art and meet accreditation standards, and advising and mentoring students—take an equally great deal of time.

For most faculty members, time is in severely short supply. If research offers the promise of substantial rewards and career advancement and teaching offers little more than internal self-satisfaction, the only faculty members likely to engage in educational reform are those already deeply committed to teaching excellence. The number of such faculty members has grown rapidly in the past twenty years, but it is still too small to achieve reform of the magnitude that will be required to meet the demands on engineering education expected in the coming decades.[1]

We believe that most university faculty genuinely want to be good teachers. Their desire is not motivated by the prospect of external rewards but by intrinsic motivators such as the sense of accomplishment that comes from equipping students with new skills and self-confidence.

For all but the most dedicated, however, intrinsic motivation to teach as well as one can eventually diminishes if the campus culture offers little more than empty rhetoric and a few awards to demonstrate its commitment to excellence in teaching. Sloan[20] suggests—and we agree—that external recognition and rewards for effective teaching are needed to support and reinforce intrinsic motivation to teach well. Gmelch, *et al.*,[21] and Boyer[22] support this idea, identifying inadequate recognition and reward as a major contributor to faculty stress and burnout.

The need to improve the campus climate for teaching is emphasized in a 1999 report of the National Research Council on transforming education in Science, Mathematics, Engineering, and Technology (SME&T).[23] The fifth "vision" articulated in this report speaks directly to the point:

> *Vision 5: All postsecondary institutions would provide the rewards and recognition, resources, tools, and infrastructure necessary to promote innovative and effective undergraduate SME&T teaching and learning.*

The report notes that if Vision 5 were to be realized, universities "would recognize and appropriately reward faculty leaders and departments or program units that have introduced new teaching and learning methods into their courses and curricular programs," recognition and rewards that the Council clearly believes are not currently in place.

Motivated by pressures from respected organizations like the NRC and from industry, governing bodies, and accrediting agencies, many academic programs at research universities have instituted measures to improve teaching. Brent and Felder[24] have assembled a list of such measures, which we summarize below. The more of these measures in place on a campus, the more likely the faculty will be to play an active role in efforts to reform engineering education.

To avoid excessive repetition, in the remainder of this

section we will use "teaching" to be a catch-all term covering classroom instruction, advising and mentoring undergraduate students, mentoring faculty colleagues and graduate students in teaching, and educational scholarship.

❑ ***To encourage and help faculty to improve their teaching effectiveness:***

- Provide funds for travel to education-related workshops and conferences.
- Provide internal grant support—summer salary and/or materials/supply money—for faculty who propose to carry out a specific project related to their teaching effectiveness.
- When giving new faculty start-up money, designate some of it for teaching-related activities
- Purchase good books on teaching—*e.g.,* McKeachie[25] and Boice[26]—and give them to new faculty members, perhaps in conjunction with an orientation workshop.
- Establish and support a Engineering Center for Teaching and Learning that sponsors a variety of teaching improvements for new faculty, experienced faculty, and graduate students.[27] Alternatively, if a campus-wide center already exists, establish a half-time or full-time engineering faculty development coordinator to work with Center personnel on programs specifically for engineers and to help involve engineers in suitable campus-wide programs.
- Institute a Teaching Leaders program in which outstanding engineering teachers are identified and compensated for jointly facilitating teaching courses, seminars and workshops with faculty development personnel[4] and serving as mentors to new faculty members.[4,28]
- Establish an Engineering Teaching Fellows program in which faculty members in their first few years of teaching receive observation and individual consulting by teaching center personnel and regularly attend seminars or learning communities devoted to good teaching and educational scholarship. Provide stipends, travel funds, or some other tangible form of support to the teaching fellows.

❑ ***To encourage faculty to redesign curricula and courses (e.g. for distance education or Web-based instruction):***

- Offer summer salary, release time during the semester, and/or the assistance of a graduate student or work-study student for planning the redesign and preparing new instructional materials.
- Offer and support faculty participation in intensive, personalized summer programs with a specific focus (*i.e.,* teaching and learning via the Web).
- Provide funds for a retreat to a team of faculty working on course or program redesign.

❑ ***To encourage departments to improve teaching or undertake curriculum renewal:***

- Devote some of the regular departmental or college seminars to topics related to teaching.
- Identify graduate TA's to help faculty members to incorporate technology (*e.g.,* design a course Web site and put class materials on it, design tutorials to help students with a new piece of software) or to update their courses specifically to address accreditation criteria.
- Establish a college of engineering reserve fund to support multi-faculty departmental initiatives to improve instruction, courses, and curricula and to reward departments that demonstrate the success of the initiatives using systematic assessment.

❑ ***To reward faculty members for excellence in teaching, advising, mentoring, and educational scholarship:***

- Require faculty members seeking tenure and/or promotion to prepare a teaching portfolio containing evidence of teaching effectiveness and educational scholarship.[5] Have multiple evaluators rate the portfolio using a standardized rating form and reconcile their ratings. Include the results in a meaningful way when making tenure and promotion decisions.
- Hold workshops or seminars for senior faculty involved in making tenure and promotion decisions to teach them how to evaluate teaching documentation.
- In preparation for evaluation, early in the school year have faculty determine a percentage for each aspect of their jobs (teaching, research, service, extension) and goals related to each part. Base evaluations and salary recommendations on the predetermined percentage. Percentages might change from year to year as faculty members explore new research and teaching projects and move into new phases of their careers.
- Allocate a portion of merit raise funds for outstanding teaching or mentoring.
- Establish numerous small awards and several large

awards ($5000 or more) to reward excellence in teaching, advising, mentoring, and educational scholarship.

- Recognize teaching achievements at faculty and advisory board meetings and in departmental and university publicity releases.

Adopting some of these suggestions can enable an institution to improve the quality of its instructional program substantially, especially if the suggestion about taking teaching into account in tenure and promotion decisions is one of those adopted.

SUMMARY

The devaluation of teaching in the faculty incentive and reward structure of most research universities that began four decades ago has begun to reverse; however, much remains to be done before the educational reforms suggested in this series of papers can become part of the mainstream of engineering education. The key is to provide instructional development that informs faculty members about alternatives to traditional teaching and assessment methods—what they are, what the evidence is for their effectiveness, and how they can be implemented without taking excessive preparation time or having to sacrifice important course content.

The time demands imposed by the adoption of student-centered instructional approaches like active, cooperative, and problem-based learning can be minimal as long as new methods are introduced gradually, starting with techniques that do not require much preparation or class time. For example, instructors might motivate the presentation of new course topics with short industrially relevant case studies, hand out instructional objectives in the form of study guides for one or more tests, and include some brief active exercises in class.

To compensate for the additional class time taken by these instructional techniques, the instructors can put portions of the lecture notes in handouts or a coursepack, including gaps and questions to be addressed in or out of class. The time saved by not having to say and write everything in the lecture notes should be sufficient to allow as many active learning exercises as the instructor wishes to assign.

Another concern that makes faculty members reluctant to move to more student-centered instructional approaches is the fear (often based on experience) of student aversion to these methods. Starting slowly and gradually increasing the use of such approaches serves to minimize student resistance. Instructors should also explain to the students what they plan on doing and their reasons for doing it, including some published research results attesting to the learning benefits of the approach to be used. Instructors should also avoid rigidity in the application of the methods, recognizing that some students have unique time constraints and other problems that should be dealt with on an individual basis.

Convincing faculty members that alternative teaching and assessment approaches lead to effective learning and addressing their concerns about implementation of the approaches are necessary but not sufficient conditions for educational reform. Before most engineering faculty members will be willing to invest much time and energy to improve teaching, they must be convinced that teaching improvement is truly valued by their institution and that their efforts will not limit their prospects for tenure and promotion.

A list of possible steps that institutions can take to communicate that message is presented in this paper. The steps include establishing and supporting workshops and mentorships for new faculty members and graduate students, providing grants and release time for efforts to update and improve the effectiveness of curricula and courses, recognizing and meaningfully rewarding excellence in teaching, advising, mentoring, and educational scholarship, instituting formal procedures for assessing teaching performance and educational scholarship, and taking the results into account when making decisions on tenure, promotion, and merit raises. The latter step alone could be sufficient to raise the quality of an institution's instructional program to a level that exceeds the expectations of the most idealistic proponents of educational reform.

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We are pleased to have been chosen as the vehicle of information and discussion for this important series. As we enter this new millennium, we hope that it will inspire chemical engineering educators to seek ways to enhance the learning experience of all their students.

AN ALTERNATE METHOD FOR TEACHING AND IMPLEMENTING DIMENSIONAL ANALYSIS

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When my daughter was a little girl, her mother asked, "Whom do you love most, mommy or daddy?" My daughter gave the politically correct answer "I love you both equally." But then her mother (who is a mathematician!) asked, "But who is more equal?" My daughter tactfully responded, "You are, mommy!" Some might contend that dimensional analysis is elementary and that all approaches are equal. If so, my response is that there is a "more equal" approach if one can write down the describing equations. This approach is an alternative to the Pi Theorem method that involves the following three steps

1. *List all qualities on which the phenomenon depends.*
2. *Write the dimensional formula for each quantity.*
3. *Demand that these quantities be combined into a functional relation that remains true independently of the size of the units.*

In Step 3, one invokes the Pi Theorem, which states that n - m dimensionless groups are formed from n quantities expressed in terms of m units. A proof of the Pi Theorem and discussion of the special case n = m are given in Bridgman.[1]

Unfortunately, using the Pi Theorem approach is not always straightforward. For example, how do we select the quantities? When do we include dimensional constants such as g_c (Newton's Law constant), R (gas constant), etc? How are dimensionless quantities such as angles involved? How many units must be considered? For example, force can be considered a primary quantity expressed in units of its own kind (*e.g.,* Newton's), or a secondary quantity expressed in terms of mass, length, and time (*e.g.,* $kg \cdot m/s^2$). This problem also arises with quantities involving energy or temperature units, since both can be considered either as primary or secondary quantities. If one can write the describing equations, the approach proffered here can be used to avoid the aforementioned difficulties.

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AN ALTERNATIVE METHOD FOR DIMENSIONAL ANALYSIS

The procedure for this method is as follows:

1. Write the algebraic and/or differential equations needed to solve the problem.
2. Write any required initial, boundary, and auxiliary conditions.
3. Use all available information in order to simplify the equations in steps 1 and 2.
4. Define dimensionless dependent and independent variables using arbitrary scale and reference factors.
5. Nondimensionalize the equations, initial, boundary, and auxiliary conditions in steps 1 and 2.
6. Determine the scale and reference factors by setting dimensionless groups equal to one (for scale factors) or zero (for reference factors); this yields the minimum parametric representation in the form

$$f(\Pi_1, \Pi_2, \ldots, \Pi_k) = 0 \qquad (1)$$

   where Π_i denotes a dimensionless group. These Π_i s include dimensionless groups formed from combinations of the physical and geometric quantities and any dimensionless independent variables; the latter will not appear if they are integrated out or evaluated at fixed spatial or temporal conditions.
7. The dimensionless groups in step 6 are not unique; it

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may be advantageous to isolate two dimensional quantities into one group (if possible) in order to determine their interdependence. This is done by forming a new group from the k dimensionless groups via the operation

$$\Pi_p = \beta \bullet \Pi_1^a, \Pi_2^b, \ldots, \Pi_k^j \qquad (2)$$

where β is a constant, and a,b,...,j are constants chosen to isolate the desired quantities into the new dimensionless group Π_p; one can use this new group along with any k - 1 of the original groups; however, this operation cannot result in eliminating a dimensional quantity from the analysis.

8. The number of groups can be reduced further when a Π_i is either very large or very small by expanding Eq. (1) in a Taylor series in the small (or reciprocal of a large)

$$f(\Pi_1, \Pi_2, \ldots, \Pi_k) = f\big|_{\Pi_i = 0} + \left.\frac{\partial f}{\partial \Pi_i}\right|_{\Pi_i = 0} \Pi_i + O(\Pi_i^2) \qquad (3)$$

If Eq. (3) can be truncated at the first term, the correlation will be a function of k - 1 Π_i s.

This method is closely related to scaling analysis.[2,3] It differs, however, in that no attempt is made to insure that the dimensionless quantities are of order one.

This approach is not new—indeed, Bird, *et al.,* have outlined the technique.[4] Hellums and Churchill[5] also used it to achieve the minimum parametric representation and to identify similarity transformations. This approach has also been suggested in two articles in *Chemical Engineering Education.* Andrews[6] commented, "The subject is best taught by writing down known equations as relations between dimensionless groups," and Churchill[7] stated "Dimensional analysis is most powerful when it is applied to a complete mathematical model in algebraic (differential and/or integral) form..."

Despite this recognition that dimensional analysis is "best taught" and "most powerful" when applied to a complete model, no article has appeared in *Chemical Engineering Education* describing the approach in detail. The latter is the principal goal of this paper. It will also indicate how this approach, when combined with asymptotic analysis, can lead to useful limiting forms. In addition, this paper will indicate how dimensional analysis can be combined with empirical results to obtain information about the functional form of a dimensionless correlation. Finally, it will dispel the notion that dimensional analysis is somehow limited to fluid dynamics and will provide examples drawn from heat and mass transfer!

This alternative method will be illustrated via four examples. The first will be shown in detail while the others will be outlined. The Pi Theorem approach will also be applied to each example, but in doing this, a less general approach typical of that often used by students who have limited experience will be invoked. The author has found that the Pi Theorem can be used to obtain the same result as that of the alternative method proffered here. Far more physical insight is required, however, to achieve the most general result using the Pi Theorem. There are two principal problems in using the Pi Theorem. The first involves Step 3 and the second relates to choosing the proper units. Some believe that the choice of fundamental units is arbitrary. This misconception is the source of much confusion concerning the Pi Theorem and is the cause of many of its alleged violations. For example, in the system of statics, one **must** use the units of force, mass, length, and time, and **should not** introduce the dimensional constant g_c. In contrast, in the system of dynamics, if one introduces force, mass, length, and time as the units, one **must** introduce the dimensional constant g_c, since these units are interrelated by Newton's law of motion. For example, one must introduce g_c if one uses SI units for the quantities involved in a dynamical system, since this system considers force, mass, length, and time as primary quantities.

These subtle aspects of dimensional analysis are discussed in Bridgman,[1] which should be required reading for anyone interested in dimensional analysis. But the need to know these subtleties can be avoided by using the alternative approach suggested here. As such, this alternative method is ideally suited as a teaching tool to give students a working knowledge of dimensional analysis, Its implementation, as well as other judicious operations useful in dimensional analysis, will be illustrated.

TERMINAL VELOCITY OF A SPHERICAL PARTICLE FALLING THROUGH A VISCOUS LIQUID

We seek to correlate the terminal velocity, V_t, of a spherical particle of radius R and density ρ_s falling owing to gravitational acceleration, g, through an incompressible Newtonian liquid having density ρ and viscosity μ, as shown in Figure 1. We obtain V_t from a force balance on the sphere given by

$$-\iint_S \vec{\delta}_z \cdot \vec{\delta}_r \left[P\underline{\underline{\delta}} - \mu\left(\nabla\vec{V} + \nabla\vec{V}^* \right) \right]_{r=R} dS + (\rho_s - \rho) g \frac{4}{3}\pi R^3 = 0 \quad (4)$$

where $\vec{\delta}_i$ is the unit vector in the i-direction, S is the surface area, $\underline{\underline{\delta}}$ is the identity tensor, P is the dynamic pressure, $\vec{V}$ is the fluid velocity, and * denotes the transpose. In order to carry out the integration in Eq. (4), one would have to solve the equations of motion in spherical coordinates with boundary conditions consisting of no-slip at the sphere surface and a far-field velocity condition. In a coordinate system attached to the sphere, these are given by

$$\rho\vec{V}\cdot\nabla\vec{V} = -\nabla P + \mu\nabla^2\vec{V} \quad (5)$$

$$\vec{V} = 0 \quad \text{at} \quad r = R \quad (6)$$

$$\left.\begin{aligned} \vec{V}\cdot\vec{\delta}_r &= -V_t \cos\theta \\ \vec{V}\cdot\vec{\delta}_\theta &= -V_t \sin\theta \end{aligned}\right\} \quad \text{as } r \to \infty \quad (7)$$

where r and θ denote the radial and circumferential coordinates, respectively.

Define the following dimensionless variables:

$$\hat{\vec{V}} \equiv \frac{\vec{V}}{V_s} \qquad \hat{P} \equiv \frac{P}{P_s} \qquad \hat{\nabla} \equiv L_s\nabla \qquad \hat{S} \equiv \frac{S}{L_s^2} \quad (8)$$

where ^ denotes a dimensionless variable, and V_s, P_s, and L_s denote velocity, pressure, and length scales that will be chosen to obtain the minimum parametric representation. Introducing these into Eqs. (4-7) and dividing through by the dimensional coefficient of one term in each equation yields

$$-\iint_{\hat{S}} \vec{\delta}_z \cdot \vec{\delta}_n \left[\frac{P_s L_s}{\mu_s V_s}\hat{P}\underline{\underline{\delta}} - \left(\nabla\hat{\vec{V}} + \nabla\hat{\vec{V}}^* \right) \right]_{\hat{r}=\frac{R}{L_s}} d\hat{S} + \frac{(\rho_s - \rho) g \frac{4}{3}\pi R^3}{\mu V_s L_s} = 0 \quad (9)$$

$$\frac{\rho V_s L_s}{\mu}\hat{\vec{V}}\cdot\nabla\hat{\vec{V}} = -\frac{P_s L_s}{\mu V_s}\nabla\hat{P} + \nabla^2\hat{\vec{V}} \quad (10)$$

$$\hat{\vec{V}} = 0 \quad \text{at} \quad \hat{r} = \frac{R}{L_s} \quad (11)$$

$$\left.\begin{aligned} \hat{\vec{V}}\cdot\vec{\delta}_r &= -\frac{V_t}{V_s}\cos\theta \\ \hat{\vec{V}}\cdot\vec{\delta}_\theta &= -\frac{V_t}{V_s}\sin\theta \end{aligned}\right\} \quad \text{as} \quad \hat{r} \to \infty \quad (12)$$

One possible set of scale factors is obtained by setting the following dimensionless groups equal to one:

$$\frac{R}{L_s} = 1 \Rightarrow L_s = R \qquad \frac{V_t}{V_s} = 1 \Rightarrow V_s = V_t \qquad \frac{P_s L_s}{\mu V_s} = 1 \Rightarrow P_s = \frac{\mu V_t}{R} \quad (13)$$

Hence, the solution to Eq. (10) will depend on $\hat{r}$, θ, and the dimensionless group $\rho V_t R/\mu$. When this solution is substituted into Eq. (9), evaluated at $\hat{r} = 1$, and integrated over the surface area, the resulting solution for the dimensionless

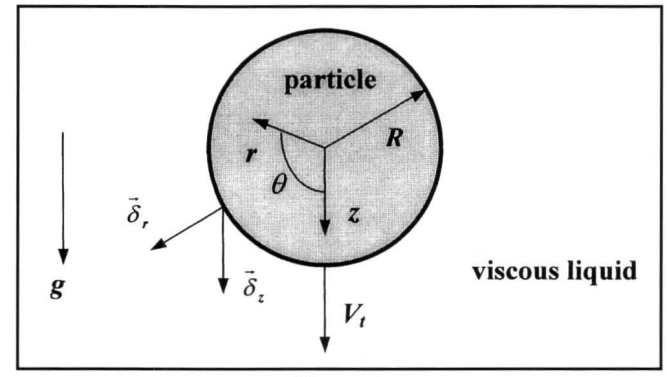

Figure 1.
Spherical particle falling through a viscous liquid.

terminal velocity can be correlated in terms of the following two dimensionless groups:

$$\Pi_1 \equiv \frac{(\rho_s - \rho) g R^2}{\mu V_t} \quad \text{and} \quad \Pi_2 \equiv \frac{\rho V_t R}{\mu} \left(\text{a Reynolds number}\right) \quad (14)$$

Hence, either data or a numerical solution for V_t can be correlated in terms of Π_1 and Π_2. These are not optimal, however, if one is seeking a correlation for V_t, since it appears in both groups. By invoking the transformation in Step 7 with a=1 and b=1 in Eq. (2), a new dimensionless group, Π_3, not containing V_t, can be obtained:

$$\Pi_3 \equiv \frac{(\rho_s - \rho)\rho g R^3}{\mu^2} \quad (15)$$

Hence, data or numerical results for V_t can be correlated in terms of Π_3 and either Π_1 or Π_2.

A naïve application of the Pi Theorem with n=6 and m=3 (or n=7 and m=4 if F is also used as a unit and g_c included as a quantity) indicates that the correlation for V_t requires three rather than two dimensionless groups. In order to obtain the most general result from the Pi Theorem, one must recognize that g appears as the product $g(\rho_s - \rho)$. The alternative approach suggested here avoids these subtleties associated with the Pi Theorem method.

Standard references[4] suggest that V_t can be correlated in terms of just Π_1; that is

$$V_t = \frac{2R^2 g(\rho_s - \rho)}{9\mu} \Rightarrow \Pi_1 = \frac{(\rho_s - \rho) g R^2}{\mu V_t} = \frac{9}{2} \quad (16)$$

This is for the special case of creeping flow for which the intertia terms can be neglected, however. Hence, Π_2 (or equivalently Π_3) no longer appears in the minimum parametric representation. Note, a naïve application of the Pi Theorem would suggest three dimensionless groups (n=6 and m=3). But the Pi Theorem will predict one group if one recognizes that g appears as the product $g(\rho_s - \rho)$ and that F **must** be introduced as a unit (without including g_c), since creeping flow is a problem in statics. Clearly, the alternative approach proffered here obviates the need to be aware of

these special considerations required to get the most general result using the Pi Theorem.

A simpler way to obtain this result is to use Step 8. Since creeping flow implies $Re = \Pi_2 \to 0$, the expansion must use groups Π_1 and Π_2. In the limit of $\Pi_2 \to 0$ one obtains that V_t can be correlated solely in terms of Π_1.

FALLING-HEAD METHOD FOR DETERMINING THE PERMEABILITY OF A POROUS MEDIUM

The falling-head method is used to determine permeability of soils. This test, shown in Figure 2, involves driving a pipe of radius R into the soil until it penetrates the water table, which is shown here at the exit of the tube. The pipe is filled with water to a height L_i and the time t_D required to drain it to a height L_f is measured. The draining time t_D is related to the axial velocity V_z and Darcy's law via the equation

$$(L_i - L_f) = -\int_0^{t_D} V_z\Big|_{z=0} dt = \int_0^{t_D} \frac{k}{\mu}\left(\frac{\partial P}{\partial z} + \rho g\right)\Bigg|_{z=0} dt \qquad 0 \le r \le R \quad (17)$$

where k is the permeability, μ is the viscosity, ρ is the density, and g is the gravitational acceleration. The incompressible continuity equation implies that the pressure, P, is obtained from a solution to the axisymmetric Laplace's equation in cylindrical coordinates:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right) + \frac{\partial^2 P}{\partial z^2} = 0 \qquad (18)$$

This is subject to the boundary conditions

$$P = P_{atm} + \rho g L(t) \quad \text{at} \quad z = 0, \quad L_f \le L(t) \le L_i \quad 0 \le r \le R \quad (19)$$

$$P = P_{atm} \quad \text{at} \quad z = 0, \quad R \le r < \infty \qquad (20)$$

$$V_z = -\frac{k}{\mu}\frac{\partial P}{\partial z} = 0 \quad \text{as} \quad z \to \infty, \quad 0 \le r < \infty \qquad (21)$$

$$V_r = -\frac{k}{\mu}\frac{\partial P}{\partial r} = 0 \quad \text{at} \quad r = 0, \quad -\infty < z \le 0 \qquad (22)$$

$$P = P_{atm} - \rho g z \quad \text{as} \quad r \to \infty, \quad -\infty < z \le 0 \qquad (23)$$

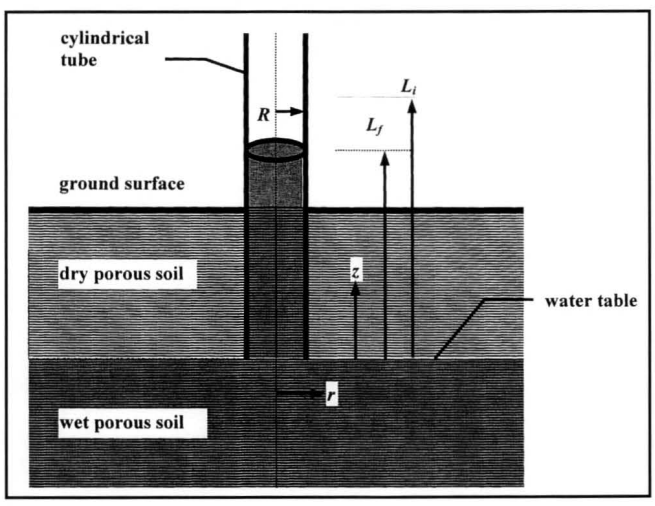

Figure 2. *Falling-head apparatus for measuring the permeability of a soil.*

Applying Steps 4, 5, and 6 leads to the following dimensionless variables:

$$\hat{P} \equiv \frac{P - P_{atm}}{\rho g L_i} \quad \hat{r} \equiv \frac{r}{R} \quad \hat{z} \equiv \frac{z}{L_i} \quad \hat{L} \equiv \frac{L}{L_i} \quad \hat{t} \equiv \frac{k\rho g t}{\mu(L_i - L_f)} \qquad (24)$$

Note that the solution to the dimensionless form of Eq. (18) will give the pressure as a function of $\hat{t}$, $\hat{r}$, and $\hat{z}$. But when the pressure is substituted into the dimensionless form of Eq. (17), evaluated at $\hat{z}$=0, and the integration carried out, the resulting solution will contain only three dimensionless parameters. This is the minimum parametric representation and implies that k is correlated in terms of t_D as follows:

$$\Pi_1 \equiv \frac{k\rho g t_D}{\mu(L_i - L_f)} = f\left(\frac{R}{L_i}, \frac{L_f}{L_i}\right) = f(\Pi_2, \Pi_3) \qquad (25)$$

A naïve application of the Pi Theorem would give five dimensionless groups (*i.e.,* n=8 and m=3)! Equation (25) can be obtained from the Pi Theorem if one recognizes that $k\rho g/\mu$ can be considered as a single quantity, thereby giving two groups (*i.e.,* m=5 and n=2).

Equation (25) can be cast into a more useful form by using an empirical correlation obtained using water and a 5-cm radius pipe for a soil having a $k = 5.9 \times 10^{-6} cm^2$:[8]

$$t_D = 4.94\,\ell n\left(\frac{L_i}{L_f}\right) \qquad (26)$$

It is convenient to recast Eq. (25) in terms of a new dimensionless group that does not contain L_i and L_f:

$$\Pi_4 \equiv \frac{\Pi_1}{\Pi_2} = \frac{t_D k\rho g}{\mu R\left(1 - \frac{L_f}{L_i}\right)} = f(\Pi_2, \Pi_3) \Rightarrow \frac{t_D k\rho g}{\mu R} \equiv \Pi_5 = f(\Pi_2, \Pi_3) \qquad (27)$$

If $R \ll L_i$, then $\Pi_2 \ll 1$, and it follows that

$$\frac{t_D k\rho g}{\mu R} \equiv \Pi_5 = f(\Pi_3) \qquad (28)$$

Comparing Eq. (28) with Eq. (26) then implies that

$$t_D = \Pi_5\left(\frac{\mu R}{k\rho g}\right) = -4.94\,\ell n\,\Pi_3 \qquad (29)$$

Hence, if $\Pi_2 \ll 1$, the generalized correlation relating k and t_D is obtained by substituting values for the quantities in Eq. (29) and is given by

$$\Pi_5 = -\frac{4.94\left(5.9 \times 10^{-6} cm^2\right)\left(1\frac{g}{cm^3}\right)\left(980\frac{cm}{s^2}\right)}{\left(0.01\frac{g}{cm \cdot s}\right)(5cm)}\,\ell n\,\Pi_3 = -0.572\,\ell n\,\Pi_3 \qquad (30)$$

In this case, an enlightened approach to dimensional analysis in combination with data for a specific falling-head test gives the functional form of the generalized t_D correlation in

terms of the relevant parameters; *i.e.,* Eq. (30) applies for any falling-head test for which $\Pi_2 << 1$, irrespective of the fluid, pipe size, and soil.

DESIGN EQUATION FOR ROASTING TURKEY

Mom and Dad are planning to roast turkey for the entire clan and need to know the cooking time, t_C, for the 28-lb bird shown in Figure 3. The cookbook provides the information shown in Table 1.[9] This is your opportunity to impress them with what you have learned by using dimensional analysis to generalize Table 1. Assume that it takes p geometric parameters to characterize the shape of a turkey and that all turkeys are geometrically similar. Hence, the p-1 dimensionless geometric ratios characterizing turkeys will be the same. One need only include one geometric quantity such as some characteristic body dimension, L, along with the quantities that characterize the heat transfer in the dimensional analysis. Roasting turkey involves a constant oven temperature T_S (325°F[9]). The bird is done when the center of the stuffing reaches a temperature T_0 (165°F[9]). The heat transfer is limited by heat conduction through the bird and stuffing, whose thermal conductivities and diffu-sivities are k_B, k_S, and α_B and α_S, respectively, and are assumed constant for all turkeys. Hence, t_C is obtained from a solution to the three-dimensional unsteady-state conduction equation in the turkey and the stuffing:

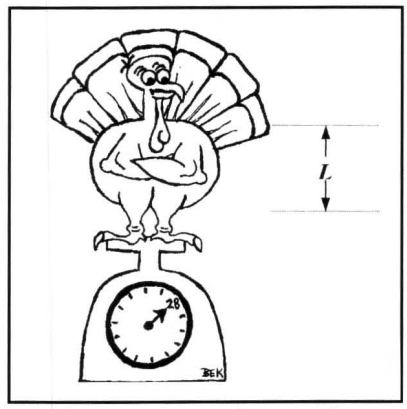

Figure 3. *A very large turkey having a characteristic length L.*

TABLE 1
Timetable for Roasting Turkey[9]

Ready-to-Cook Weight W (lb)	*Approximate Total Cooking Time t_C (hr)*
6 to 8	3 to 3 ½
8 to 12	3 ½ to 4 ½
12 to 16	4 ½ to 5 ½
16 to 20	5 ½ to 6 ½
20 to 24	6 ½ to 7

$$\frac{\partial T}{\partial t} = \alpha_B \nabla^2 T \tag{31}$$

$$\frac{\partial T}{\partial t} = \alpha_S \nabla^2 T \tag{32}$$

The initial and boundary conditions are given by

$$T = T_I \text{ at } t = 0 \tag{33}$$

$$T = T_S \text{ at the surface of the turkey} \tag{34}$$

$$T\big|_+ = T\big|_- \text{ at the interface between turkey and stuffing} \tag{35}$$

$$k_B \nabla T\big|_+ = k_S \nabla T\big|_- \text{ at the interface between turkey and stuffing} \tag{36}$$

$$\nabla T = 0 \text{ along the plane of symmetry in the turkey} \tag{37}$$

Applying Steps 4, 5, and 6 leads to the following dimensionless variables:

$$\hat{T} \equiv \frac{T - T_I}{T_S - T_I} \quad \hat{t} \equiv \frac{t\alpha_B}{L^2} \quad \hat{\nabla}^2 \equiv L^2 \nabla^2 \tag{38}$$

Introducing these variables into Eqs. (31-37) implies the following minimum parametric representation:

$$\frac{t_C \alpha_B}{L^2} = f\left[\frac{(T_0 - T_I)}{(T_S - T_I)}, \frac{\alpha_B}{\alpha_S}, \frac{k_B}{k_S}, \ldots, \text{geometric ratios}\right] \tag{39}$$

Hence, for geometrically similar turkeys and constant physical properties, $t_C \propto L^2$. For a spherical turkey body, $L \propto W^{1/3}$. Hence, $t_C = KW^{2/3}$, where K is a proportionality constant determined from the data in Table 1. The following correlation fits these data with an $R^2 = 0.994$:

$$t_C = 0.864\, W^{2/3} \tag{40}$$

Hence, Mom and Dad's 28-lb bird will require a $t_C = 8$ hours. Note that a naïve application of the Pi Theorem would imply five dimensionless groups (*i.e.,* n=9 and m=4) in addition to the geometric ratios.

DESIGN OF A NOVEL MEMBRANE BLOOD OXYGENATOR

A recent patent describes a hollow fiber membrane blood oxygenator that offers a 300% increase in O_2 and CO_2 mass transfer.[10] This is achieved by oscillating the hollow fiber membrane module relative to the blood flow. This enhances the mass transfer on the blood side where O_2 diffusion is limiting. We seek to correlate the mass-transfer coefficient for this device by considering a single oscillating hollow fiber as shown in Figure 4.

An analytical solution has been developed for the hydrodynamics when the membrane tube bundle is pulsated harmonically at a frequency ω and amplitude A; the velocity profile, $\hat{V}_z$, is of the form[11]

$$\hat{V}_z \equiv \frac{V_z}{\overline{V}} = f\left(\frac{r}{R}, \omega t, \frac{\nu}{\omega R^2}, \frac{A\omega}{\overline{V}}\right) \tag{41}$$

where $\overline{V}$ is the volume-average velocity, R is the hollow-fiber radius, ν is the kinematic viscosity of the Newtonian fluid, and t is the time. We seek a correlation for the mass-transfer coefficient defined in terms of the log-mean driving force, ΔC_{lm}, and the overall length of the tube, L, as follows:

$$k_L \equiv \frac{\overline{N}_w}{\Delta C_{lm}} = \frac{\omega D}{2\pi L \Delta C_{lm}} \int_0^{2\pi/\omega} \int_0^L \left.\frac{\partial C}{\partial r}\right|_{r=R} dz\,dt \tag{42}$$

where

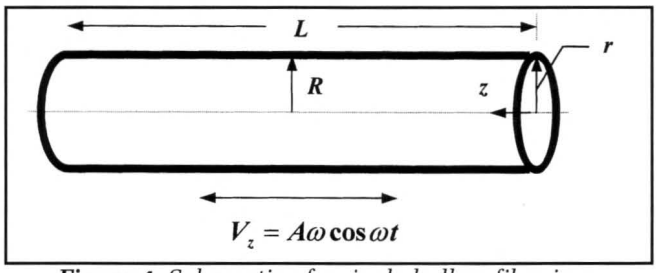

Figure 4. *Schematic of a single hollow fiber in a membrane lung oxygenator.*

$$\Delta C_{lm} \equiv \left[(C_W - C_L) - (C_W - C_O)\right] \Big/ \ell n \frac{(C_W - C_L)}{(C_W - C_O)} \tag{43}$$

in which $\overline{N}_w$ and C_w are the mass-transfer flux and concentration, respectively, at the blood side of the membrane, C_o and C_L are the concentrations at z=0 and z=L, respectively, where L is the length of the hollow fiber, and D is the binary diffusion coefficient. The concentration in Eq. (42) is obtained from a solution to the axisymmetric form of the advective diffusion equation in cylindrical coordinates:

$$\frac{\partial C}{\partial t} + V_z \frac{\partial C}{\partial z} = \frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) \tag{44}$$

Axial diffusion is neglected based on scaling arguments.[2,3] The boundary and periodic solution conditions are

$$C = C_W \quad \text{at } r = R \tag{45}$$

$$\frac{\partial C}{\partial r} = 0 \quad \text{at } r = 0 \tag{46}$$

$$C = C_O \quad \text{at } z = 0 \tag{47}$$

$$C_{t,r,z} = C\big|_{t+2\pi/\omega,r,z} \tag{48}$$

Applying Steps 4,5, and 6 leads to the following dimensionless variables:

$$\hat{C} \equiv \frac{C - C_O}{C_W - C_O} \quad \hat{r} \equiv \frac{r}{R} \quad \hat{z} \equiv \frac{z}{L} \quad \hat{t} \equiv \omega t \tag{49}$$

Introducing these into Eqs. (42) and (44) leads to

$$\frac{k_L R}{D} \equiv Sh = -\frac{\ell n\left(1 - \hat{C}_L\right)}{2\pi \hat{C}_L} \int_0^{2\pi}\int_0^1 \frac{\partial \hat{C}}{\partial \hat{r}}\bigg|_{\hat{r}=1} d\hat{z}d\hat{t} \tag{50}$$

$$\frac{\omega R^2}{D}\frac{\partial \hat{C}}{\partial \hat{t}} + \frac{2Gz}{\pi}\hat{V}_z \frac{\partial \hat{C}}{\partial \hat{z}} = \frac{\partial}{\partial \hat{r}}\left(\hat{r}\frac{\partial \hat{C}}{\partial \hat{r}}\right) \tag{51}$$

where $Gz \equiv \pi \overline{V} R^2 / 2DL = \pi RPe/2L$ is the Graetz number and Pe is the Peclet number. Equation (50) implies that Sh, the Sherwood number, is a function of the dimensionless groups involved in determining $\hat{C}_L$ and $\partial\hat{C}/\partial\hat{r}$ at the fiber wall and hence will be functions of only the dimensionless groups involved in solving Eq. (51); therefore

$$Sh = f\left(Gz, \frac{\omega R^2}{D}, \frac{\omega R^2}{\nu}, \frac{A\omega}{\overline{V}}\right) \text{ or } Sh = f\left(Gz, Sc, \frac{\omega R^2}{D}, \frac{A\omega}{\overline{V}}\right) \tag{52}$$

where $Sc \equiv \nu/D$ is the Schmidt number, introduced by using the transformation given by Eq. (2). For large Sc (*i.e.,* for blood) we can use the expansion (in Sc^{-1}) suggested by Eq. (3) to conclude that the oxygenator performance can be correlated in terms of only four dimensionless groups. Note that a naïve application of the Pi Theorem would imply that eight dimensionless groups would be required (*i.e.,* n=11 and m=3).

EPILOGUE

The Pi Theorem will yield the minimum number of dimensionless groups, if one can determine the proper quantities and units to use. But this requires considerable physical insight, often well beyond the experience of many students. The alternative method proposed here directly yields the minimum parametric representation without having to invoke any sophisticated reasoning concerning how variables appear in certain combinations or the proper units for the particular physical system. Hence, in the words of my young daughter, it is "more equal!"

ACKNOWLEDGMENTS

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A PROJECT-BASED, SPIRAL CURRICULUM FOR INTRODUCTORY COURSES IN CHE

Part 1. Curriculum Design

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Engineering education in the United States today faces many challenges, including: 1) attracting students with a diversity of backgrounds, learning styles, and pre-college preparations for engineering careers; 2) maintaining interest and motivation during a four-year undergraduate education, while at the same time assuring quality and relevance to engineering practice; 3) preparing students for demanding careers that not only require technical competence in an engineering discipline but also require communication, teamwork, and life-long learning skills; and 4) maintaining or enhancing quality programs in the face of increasing financial pressure.[1,2] Since the traditional approach to chemical engineering education was designed for a somewhat different set of challenges, we question whether it is well suited to meet today's needs.

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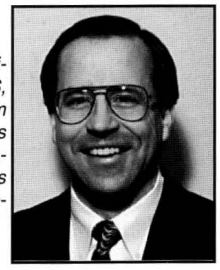

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In the traditional approach, the chemical engineering curriculum provides a compartmentalized sequence of courses that aims to build a solid, fundamental foundation before providing integrated, capstone and/or engineering practice experiences in the senior year. Problems that arise from this educational structure include

- Lack of motivation for learning fundamental material
- Poor retention of sophomore- and junior-level material that is needed for the senior-year integrated experiences
- Segmented learning resulting in a lack of ability to integrate material presented in several different courses
- Lack of ability to extrapolate knowledge and skills gained in one context (*e.g.*, thermodynamics) to a different context (*e.g.*, thermodynamic limitations in reactor design)

While cognitive science indicates that repetition is central to learning,[3] all too often important material is presented once and assumed to be "learned." Moreover, the traditional lecture format has not been conducive to accommodating different learning styles or to a desirable shift away from passive learning to active learning.[4,5]

To address the challenges and deficiencies noted above, we have developed a project-based, spiral curriculum for our chemical engineering sophomore year. The new curriculum is "spiral" because the understanding of basic concepts and their interrelations is reinforced by revisiting them in different contexts with increasing sophistication each time. It is

The new curriculum is "spiral" because the understanding of basic concepts and their interrelations is reinforced by revisiting them in different contexts with increasing sophistication each time

"project-based" because students learn and apply chemical engineering principles by actively completing a series of projects (including open-ended design projects and laboratory experiments) throughout their first year of study, rather than by simply passing a series of tests on related but compartmentalized subjects in a lecture-based course sequence.

In this series of papers we will describe the design, implementation, and evaluation of the new curriculum. This paper presents the philosophy, objectives, and curriculum design. Subsequent papers will describe the details of the projects and curriculum, our implementation experiences, and our extensive assessment efforts. Although some features of the new curriculum are unique to Worcester Polytechnic Institute (WPI), we anticipate that much of it will be transferable to other settings and timetables and that our approach can serve as a model for other engineering disciplines.

TABLE 1
Typical Schedule of WPI ChE Core Courses

	Term A	*Term B*	*Term C*	*Term D*
	(Fall Semester)		*(Spring Semester)*	
Sophomore	Material and Energy Balances	Classical Thermodynamics	Mixture Thermodynamics	Staged Separation Processes
Junior	Fluid Mechanics	Heat Transfer	Mass Transfer	Kinetics and Reactor Design
Senior	Unit Operations Laboratory I	Unit Operations Laboratory II	Process Control Laboratory	Applied Math for Chem. Eng.
	Process Design and Economics	Chemical Plant Design Project		

BACKGROUND

The problems noted above are neither newly discovered nor limited to chemical engineering. There are ongoing efforts aimed at addressing these same problems in engineering programs across the country. These efforts can be placed into three main categories that differ in approach from the one described here. First, there are programs aimed at integrating math, science, English, and engineering subjects at the freshman and sophomore level before beginning discipline-specific studies. Drexel's E^4 program, some of the National-Science-Foundation-supported Engineering Education Coalitions, and several other programs have focused on providing an active learning integrated curriculum that introduces engineering practice to freshman and sophomore students.[6-13] All of these programs focus on interdisciplinary or general engineering principles at the earliest level of engineering education, whereas our new curriculum is directed toward more in-depth study of core chemical engineering courses. The project-based, spiral curriculum could thus follow one of the newly developed interdisciplinary introductory programs, or it could follow a more traditional basic math-and-science introductory curriculum, as is currently the case at WPI.

The second type of related-but-different approach to reform is aimed at bringing the excitement of engineering design to the freshman level as a motivational introduction to engineering without necessarily reorganizing the entire freshman experience. In some cases there are cross-disciplinary "introduction to engineering" courses[14-15] and in others there are discipline-specific introductory courses.[16-17] The third type of reform effort aims to provide design across the curriculum by integrating design into existing courses throughout the curriculum.[18-21]

Virtually all of the recent reform efforts have incorporated proven learning-enhancement strategies of active, cooperative learning,[22,23] and problem-based or project-based learning.[24,25] We have also used these strategies, but what distinguishes our program is that we have completely reformed the first set of core chemical engineering courses to emphasize these features and to integrate material that is normally taught in a compartmentalized sequence of fundamental courses.

OUR TRADITIONAL CURRICULUM

WPI has an atypical academic calendar consisting of five seven-week terms; four during the regular academic year and an optional, fifth one during the summer. Normally students take three courses or activities during each of the four academic-year terms denoted terms A, B, C, and D, and complete their studies in four years. Our A and B terms correspond to Fall semester, and C and D correspond to Spring semester in other programs. The typical sequence of core chemical engineering courses encountered by our stu-

dents is presented in Table 1. During their freshman year, they study chemistry, physics, calculus, and humanities or social science electives. Their first exposure to chemical engineering begins in their sophomore year. In addition to the core material balance and thermodynamics courses shown in Table 1, they normally take physical chemistry, organic chemistry, differential equations, and more humanities and social science courses in their sophomore year. During their junior year, students usually take engineering electives and complete a three-course-equivalent "interactive qualifying project" relating science and technology to society in addition to completing the transport and reactor design courses shown in the table. During their senior year, all of our students complete a three-course-equivalent "major qualifying project," similar to a senior thesis, in addition to the unit operations, design, and control courses shown.

Although the format is different, the core content of our curriculum is similar to that of most other chemical engineering departments. We teach the fundamental subjects underlying chemical engineering process analysis and design in a compartmentalized sequence of courses during the sophomore and junior years. Then, in the senior year we ask the students to work in teams on integrated laboratory and design problems using those fundamentals. In addition to assigning complex, open-ended problems for the first time, we also emphasize teamwork and oral and written communication skills for the first time in the senior year.

This process has been likened to the following hypothetical method of training a baseball team. Suppose you take nine people who don't know the game of baseball and train them individually in all the fundamentals for two years; two months on throwing, three months on catching, five months on hitting, etc. Then, without ever having them practice, or even watch a game, you suddenly ask them to play the game properly as a team. Many would likely quit after the first few months because they didn't like throwing the ball over and over when they didn't know why they were doing it. Those that survived the program would probably play well at the end, but they'd have bruises from those first few games when they knew the fundamentals but not how to put them together.

Our students often complain that the first half of their senior year was the hardest thing they have ever done, but at the same time acknowledge that it was their best educational experience. They recognize that solving practical laboratory and design problems and communicating their results forced them to relearn and better understand the fundamentals as well as prepared them for the role of a practicing engineer. Part of our motivation for the project-based, spiral curriculum was to bring some of these rich senior-year experiences into the earlier years.

Although we have recently begun incorporating active and cooperative learning exercises within some of our courses, the format of lecture/followed by homework/followed by test, dominated the learning process. Our students use computers for word processing, spreadsheets, math packages, programming, and the process modeling and design program AspenPlus, but there is no emphasis on computer use and no specific computer skills development strategy. AspenPlus is not used until the senior-year design course.

TABLE 2

Goals of the New Curriculum

- Integrate material from our first four core courses
- Reinforce key concepts by repetition with increasing complexity
- Provide semirealistic applications of fundamentals
- Provide laboratory and design experiences
- Emphasize active learning
- Integrate computer use throughout the curriculum
- Introduce AspenPlus to sophomores
- Improve student motivation for learning fundamentals
- Improve problem-solving abilities
- Improve mastery of fundamentals
- Improve communication skills
- Improve teamwork skills
- Maintain individual accountability
- Promote lifelong learning
- Improve attitudes and satisfaction with chemical engineering
- Use computer-aided instruction and peer learning asistants to maintain costs

OUR NEW CURRICULUM

The goals of our new curriculum are listed in Table 2 and can be seen to be consistent with the goals of ABET's Engineering Criteria 2000.[26] These goals should result in students who can work effectively in teams to combine material and energy balances with thermodynamics, transport phenomena, chemical kinetics, and reaction engineering to analyze and design chemical processes.

In considering how best to achieve these goals, we used our baseball analogy and wanted students to play some practice games and enjoy what they were doing as they developed their fundamental skills. We wanted them to encounter some semirealistic chemical process analysis and design problems throughout their chemical engineering studies, rather than only at the end. We hypothesized that a series of well-structured projects could provide motivation for learning fundamentals as well as provide practical applications of those fundamentals. Integrating material throughout the cur-

riculum would reinforce interrelationships between subjects and help develop abilities to solve realistic problems.

To completely fulfill our plans, we realized, however, that the entire first two years of chemical engineering courses would have to be reorganized. Beginning knowledge and skills from several traditional courses needed early introduction to accommodate meaningful, but carefully structured, early projects. Knowledge and skills could then be added on a "just-in-time" basis to help students progress through a series of projects with increasing complexity. There was no need to change our senior year, because it already had integrated, project-based, team-oriented laboratory and design experiences.

Although we realized that integration of all material from the sophomore and junior years was important, we decided to focus only on the sophomore year. We thus sought the more modest goal of integrating material and energy balances with thermodynamics and stage-wise separation processes, hoping to produce rising juniors who could work in teams to combine these subjects to analyze and design processes, albeit those without regard to rate behavior. Reasons for neglecting to integrate the transport and reactor courses into our new curriculum included: 1) complete reform of two year's curriculum seemed unmanageable; 2) meaningful projects could be done that did not require rate information; 3) some of our transport courses are taken by non-chemical engineering students and/or are taught by non-chemical engineering professors; 4) many of our students study off-campus for one or more terms during their junior year, creating scheduling problems with a year-long integrated junior-year course; and 5) senior-year courses provide an opportunity to integrate the rate material with other topics.

Since a major revision of the sophomore year was required, we took the opportunity to introduce other desirable features into the new curriculum. As shown in Table 2, most (but not all) of the goals followed directly from our desire to produce students with the ability to "play the game" and not just those who could "hit well in batting practice." Although not a specific goal of our new sophomore-year curriculum, one additional positive outcome might be that the student's senior year becomes more enjoyable as well as more productive. This might happen because students who go through the new curriculum as sophomores will have experience with team-based integrated projects before their senior year.

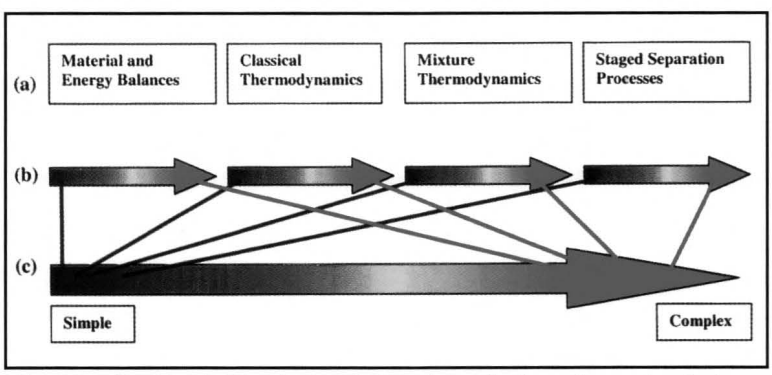

Figure 1. *Rescheduling the traditional curriculum from simple-to-complex. (a) traditional four courses; (b) within each course material flows from simple (blue) to complex (red); (c) a new year-long course with material from each of the four traditional courses rearranged from simple to complex.*

DESIGN OF THE NEW CURRICULUM

To develop our new curriculum, we itemized and prioritized detailed learning objectives for the four traditional sophomore-year courses (see Figure 1a). We noted that in each course the material progressed from simple to complex, as illustrated with the color-coding in Figure 1b. In one sense, what we sought was a year-long course that integrated topics from the four traditional courses by teaching the beginning material from each course in a new first course, followed by the intermediate material from each traditional course in a new second course, and so on, as illustrated in Figure 1c. We also wanted to revisit key concepts throughout the year and to emphasize the connection of ideas normally presented separately in separate courses. We therefore developed the "spiral" curriculum concept, shown schematically in Figure 2. The sophomore year was divided into four levels shown in the vertical direction of the diagram and corresponding to our four terms. At WPI the four levels correspond to discrete courses, but that need not be the case. For example, in a semester system, the material from levels 1 and 2 could be taught in a single 5-6 credit semester-long course.

Our four traditional courses are shown at the base of the diagram to provide a reference frame for com-

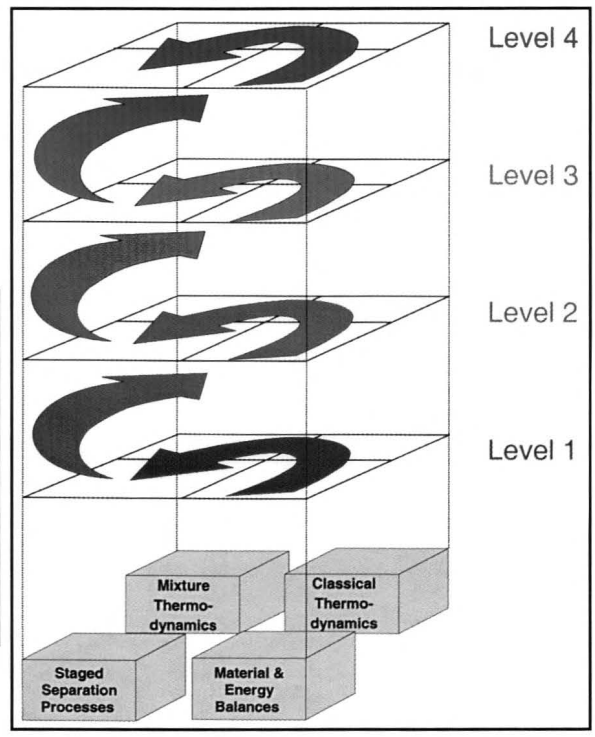

Figure 2. *Schematic diagram of the spiral curriculum.*

parison. Students begin the new curriculum at Level 1, where they are introduced to the basic skills and concepts from all four traditional courses. In Level 2, in addition to introducing new material we build on the previously acquired skills and concepts by requiring them to be re-used and extended to more complex tasks. The succeeding two levels follow similarly, with the students revisiting topics met before at lower levels, extending them to more sophisticated uses and ideas, as well as acquiring new knowledge and concepts needed to address more challenging problems.

Table 3 presents the results of prioritizing and rearranging important topics from our sophomore year into a spiral curriculum with four levels. At Level 1, we introduced simple material and energy balances with no recycle, the thermodynamics of pure components, first-law energy balances, ideal-phase equilibria, and simple flash separations. At Level 2, students were exposed to ideas of recycle, staged separation systems, and the applications of energy balances to flow systems. Non-ideal gas-phase behavior was introduced through entropy concepts in the analysis of flow processes and the use of real gas relations, including residual properties. The students' experience with separation equipment was broadened first by extensive coverage of distillation at the start of the level, followed by a short look at isothermal gas absorption toward the end. In Level 3 the focus was on the properties of mixtures, especially non-ideal solutions

TABLE 3
Curriculum Material by Level

Level *Topics*

1 ***Material balances and stoichiometry***
- unit conversions, temperature and pressure scales, mass, mole fractions
- stoichiometry, conversion, yield, limiting and excess reactants
- density; ideal gas law and partial pressure
- non-reactive material balances; choice of basis
- material balances on reactive systems; tie components

Energy balances—first law
- properties of pure fluids
- gas-liquid systems, relative saturation
- phase rule, vapor pressure, Raoult's law
- W, Q, U, 1st law for closed systems; reversible systems
- enthalpy, 1st law for steady-flow processes
- thermodynamic data: steam tables, ΔH, c_p
- heat effects for phase changes
- energy balance applications

Introduction to staged separations
- binary VLE, y-x diagram, bubble and dew-point calculations
- multicomponent VLE; K-factors
- single-stage binary flash
- single-stage multicomponent flash
- multistage distillation and external column balances
- introduction to McCabe-Thiele methods

2 ***McCabe-Thiele methods for binary distillation***
- stage-to-stage calculations
- enriching and stripping sections, feed line
- effect of reflux ratio, plate efficiency
- introduction to non-CMO methods

2nd law, thermodynamics of steady flows
- material balances on reactions, excess air
- heat effects of industrial reactions
- entropy, 2nd law of thermodynamics
- Carnot heat engine, thermal efficiency
- combined law of thermodynamics, fundamental property relations
- steady-flow processes, efficiencies of flow devices
- power cycles
- thermodynamic analysis, thermodynamic efficiencies
- refrigeration

Material balances with recycle; real gases; absorption
- material balances with recycle, purge, and by-pass
- real gases and compressibility; cubic equations of state
- real gas mixtures, Kay's rule
- critical properties, acentric factor and principles of corresponding states
- residual properties and compressor, turbine analysis
- isothermal absorption of gases in staged equipment
- Kremser equations for dilute gas absorption; plate efficiencies

3 ***Property changes on mixing***
- partial molar properties, ideal solution, and excess properties
- heat effects of mixing—heats of solution, formation
- enthalpy-concentration charts; adiabatic mixing

Solution thermodynamics and VLE
- phase rule, vapor-liquid equilibrium in ideal mixtures
- corrections to ideal-solution behavior, activity coefficient models
- excess Gibbs energy and activity coefficient models
- chemical potential and equilibrium criterion
- fugacities and fugacity coefficients
- activity coefficients and standard states
- low-pressure VLE calculations
- solubility of a gas in a liquid; VLE from EOS
- calculation of fugacity for pure components, mixtures
- azeotropes and distillation

Liquid-liquid extraction
- liquid-liquid equilibria
- immiscible extraction: LLE, single stage
- immiscible extraction: multistage methods
- miscible extraction: LLE, lever rule
- miscible extraction: single-stage and cross-flow
- miscible extraction: multistage cross-flow

4 ***Chemical reaction equilibria***
- reaction coordinate
- standard heat of reaction, standard Gibbs energy of reaction
- evaluating equilibrium constants
- relating equilibrium constants to composition
- equilibrium conversion for single reactions
- Le Chatelier's principle
- multireaction equilibria

Unsteady-state balances
- transient material and energy balances; filling tanks and cylinders
- staged batch distillation

Combined material and energy balances
- non-CMO distillation, Ponchon-Savarit method
- psychrometry; psychrometric charts; adiabatic humidification
- computer-aided material and energy balances; degrees of freedom
- simultaneous material and energy balances on reactive processes

and phase equilibria. Property changes on mixing were followed by vapor-liquid equilibria and, finally, liquid-liquid equilibria. In the latter two cases, the thermodynamic material was coupled strongly to applications involving distillation of azeotropes and liquid-liquid extraction, respectively. Finally, in Level 4, chemical reaction equilibrium was covered, followed by advanced process calculations, including unsteady material balances and simultaneous material and energy balances. We also provided brief exposure to the process simulator, AspenPlus, in Level 4.

It should be noted that Table 3 indicates the level at which a topic is first introduced. Important topics from lower levels were revisited with more sophistication at higher levels, and each level contained material from each of the four traditional courses. We attempted to distribute the traditional material evenly throughout all four levels, but this was not always possible. Material balances, for example, were introduced early in Level 1 for acyclic systems, including stoichiometry and reactive systems. Material balances on reactions were revisited in Level 2 for heat effects associated with combustion, then were more formally extended to include recycle systems. Little formal instruction on material balances took place at Level 3, but at Level 4 the topics of unsteady material balances and combined material and energy balances, with reaction, were taken up. Topics in staged separations were distributed quite successfully throughout the curriculum, coupling somewhat with the student's increasing sophistication in the use of phase equilibria. Distillation, in particular, appeared in some form in all four levels, moving from simple flash distillation to staged binary distillation to distillation of azeotropic mixtures to unsteady staged-batch columns and non-constant molal overflow operations. The hardest material to fit into the spiral form was solution thermodynamics, since it is conceptually more advanced for most students. Level 1 used Raoult's law for vapor-liquid equilibria, but we did not find it advisable to develop this theme further until Level 3, when the usual topics in VLE were covered. Nevertheless, we found that spiraling of separation processes eased the introduction of solution thermodynamics.

Important topics from lower levels were revisited with more sophistication at higher levels, and each level contained material from each of the four traditional courses. We attempted to distribute the traditional material evenly throughout all four levels, but this was not always possible.

This new curriculum forced repetition of high-priority learning objectives throughout the entire year and emphasized their connection to ideas usually presented entirely separately in a later course. Low-priority learning objectives were de-emphasized and some were omitted, subscribing to the "less is more" philosophy that prefers a clear understanding of key concepts over superficial exposure to almost everything. Thus, by the end of the year every student should realize that chemical engineers are called upon to combine material and energy balances with thermodynamic information to analyze or design processes.

The spiral curriculum was structured around a series of industrially relevant cooperative-group projects that served as a framework for achieving the learning objectives for each level. Within each level in Table 3, topics are grouped together under headings that describe projects designed for each level. In Level 1, for example, the initial project focused on material balances and stoichiometry, the second focused on energy balances, the third introduced staged separation processes. Some projects were design oriented, some were mostly analysis, and others included laboratory experiments. Project deliverables included written reports and sometimes included oral reports. The projects themselves are described in detail in the second paper of this series.

IMPLEMENTATION AND EVALUATION

We taught the spiral curriculum to one-third of the 1997-98 sophomore class and to one-half of the sophomore class in 1998-99. The other sophomores were taught by the traditional curriculum each year and were used as a comparison for assessment of our curriculum reform. The spiral curriculum was delivered through a variety of channels, including cooperative-group projects, traditional lectures, homework problems, in-class active learning sessions, interactive multimedia learning tools, and laboratory experiments. To assure individual accountability, individual homework grades were recorded and an individual test was given at the end of each project period. A thorough understanding of the projects prepared students for most of the material on the tests, but some material was covered only in supplemental lectures and homework problems. Details of our delivery methods and our implementation experiences will be given in Part 2 of this series.

Our overall project assessment goals were to evaluate how the project-based, spiral curriculum affected students' ability to: solve problems at several levels of cognition, work in teams, work independently, master the fundamentals of chemical engineering, and integrate material from several

Continued on page 233.

SPREADING THE WORD
(About Chemical Engineering)

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There is concern in the UK academic community over a decline in university applicants to chemical engineering (see Table 1). There is an almost instinctive reaction to attempt to account for the trend, but recalling Sherlock Holmes' stern injunction that to theorize in the absence of data is a "capital mistake," we shall refrain. What would constitute hard data in this case is difficult to conceive. One is dealing with opinions and views formed over long periods of time that were subject to a host of influences. Even when a clear question can be formed, such as "Why do females account for only approximately 25% of applicants?" it rapidly becomes apparent that there are no simple answers.

Fretting over the causes of the decline will, in any case, not result in any useful outcome. Our principal concern here is with describing a proposal for halting (and perhaps even reversing) the trend. It will not be an easy task, and in order to make a real impact on the situation, it will require implementation on a large scale.

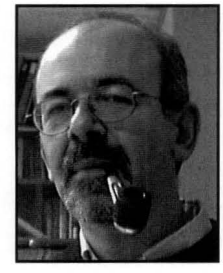
Our basic premise is that opportunities exist within the teaching of chemistry at schools to introduce information about disciplines allied to chemistry, *i.e.,* chemical engineering. We describe below a scheme intended for integration into the teaching of practical organic chemistry. Writing in the UK, we felt it logical to set out our proposal in the context of secondary-school (*i.e.,* pre-university) education in the UK. We hope that in this way the non-UK reader would be able to compare and contrast the situation existing in his or her own country with the UK problem. In addition, it should enable the reader to better determine the most appropriate age for applying the proposed project in his or her own country.

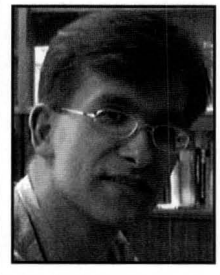
This last point is very important; we are firmly of the belief that the project work we describe (and equally important, its implementation) should be of universal applicability. One of us (KH) has recently returned from conducting, with other representatives of UK chemical engineering, a survey of academic research at the top US departments, and the opportunities to discuss other, related matters—including student recruitment—proved too great to resist. The impression gained from those informal discussions was that the US faces a broadly similar situation in declining enrollments.

BACKGROUND OF UK EDUCATIONAL STRUCTURE

Before embarking on a description of the project, we feel it is necessary to offer a brief explanation of the entry process to UK universities. The current matriculation route (excluding Scottish universities) is via the Advanced Level of the General Certificate of Education, commonly referred to as 'A' levels. At 16 years of age, prospective 'A'-level school or college candidates will have elected to sit examinations in, typically, three subjects, which they study for a period of two years. An offer of a university place is made to individual students in the form of a cumulated 'A'-level

Gilbert Shama *has been in the Department of Chemical Engineering at Loughborough for just over ten years. He has long been a member of the Departmental Admissions Team and has special responsibilities for new initiatives aimed at boosting undergraduate recruitment.*





Klaus Hellgardt *joined the Loughborough Chemical Engineering Department in 1995. He is a relatively recent recruit to the Admissions Team. He is responsible for overseas recruitment.*

TABLE 1
Applications to UK's ChE Degree Courses*

Year	Male	Female	Total
1994	1017	324	1341
1995	913	353	1266
1996	897	328	1225
1997	873	319	1192
1998	787	324	1111

**The figures shown here were derived from data supplied by the Universities and Colleges Admissions Service based in Gloucester. Under existing conditions, students may apply for entry to up to six university departments in any academic discipline. The vast majority of students apply to the maximum number of departments to study a single discipline. We have assumed this to be the case in arriving at the figures presented here.*

TABLE 2
Students Sitting 'A'-Level Examinations by Subject*

Year	Mathematics	Physics	Chemistry
1994	67,984	36,600	41,805
1995	65,892	35,234	42,836
1996	68,709	33,361	40,917
1997	70,414	33,657	42,841
1998	71,615	34,518	43,385

**Source: Qualifications and Curriculum Authority, London, 1999*

TABLE 3
Students Sitting 'A'-Level Examinations in the Combination Mathematics, Physics, and Chemistry*

Year	# of Students
1994	8,507
1995	8,762
1996	8,069
1997	8,794
1998	9,754

**Source: Qualifications and Curriculum Authority, London, 1999*

score, which may or may not be accompanied by other constraints, such as minimum grades in one or more subjects. The Scottish system is different in that students there sit the Higher Grade of the Scottish Certificate of Education ('Highers'). Students take a broader range of subjects somewhat at the expense of depth of coverage, with the consequence that courses at Scottish universities are generally correspondingly longer than those elsewhere in the UK.

'A' levels have long been criticized as requiring young people to specialize at far too early an age. This is particularly the case when compared to the majority of other European states. (There is now a real prospect of change being introduced, with the aim of maintaining educational breadth beyond the age of 16 without compromising depth. Whether or not this is achievable remains to be seen, but it is in any case outside the scope of this paper.)

The preferred combination of 'A' levels for entry into most UK chemical engineering departments is mathematics, physics, and chemistry. The number of students taking any one of these particular 'A' levels has remained relatively steady over the last five years (see Table 2). The crucially important figure, however, is the number of students presenting the combination of mathematics, physics, and chemistry (see Table 3). The encouraging feature of this data is that it shows an increase in students offering this 'A'-level combination; less encouraging is the fact that the decline in applications to chemical engineering has been occurring against the background of this increasing pool of suitably qualified young people.

THE NEED FOR RECRUITMENT PROGRAMS

Our purpose in the following proposed program of integration is to raise awareness of the discipline of chemical engineering among our young people. There are probably many ways of achieving this end, but whatever approach is taken, we feel that there are certain principles that must be upheld. The task must be seen as one of *informing* young people, not as one that attempts to entice them away from other disciplines. It has been our experience that one gains the respect of audiences of young people if one states, and adheres to, this principle.

We do not wish to be seen as claiming that the situation described here has previously gone unrecognized. It hasn't. Both professional and industrial bodies have expended considerable time and money in producing educational materials in a variety of formats, including leaflets, posters, videos, and CD-ROMs aimed at exciting interest about chemical engineering in the minds of young people. Whether or not the producers of such materials realize how fierce the competition is for those young minds is another matter.

. . . the decline in applications to chemical engineering has been occurring against [a] background of [an] increasing pool of suitably qualified young people.

Those most immediately affected by falling admissions (the universities) have responded to the situation by offer ing short residential courses aimed at giving young people "hands-on" experience in the different branches of engineering. Most of these schemes are aimed at 16-year-olds, those about to embark on their 'A' levels. The majority of these students will have already made up their minds whether they will choose Arts or Science 'A' levels. This latter group is the one from which engineering departments recruit students.

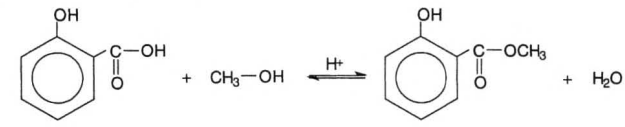
While such recruitment schemes are admirable in achieving their rather limited purpose, they can actually serve only to attract students away from the pure sciences or to redistribute students among the various engineering disciplines. This is not intended as a cynical criticism of these so-called "taster courses," since in many cases they have helped individuals form opinions about their future careers. Nor do we argue that these courses should no longer be offered. But it is evident that from a recruitment point of view, they have only limited impact, and applicants for chemical engineering continue to drop despite the existence of such courses.

It should be equally clear that the time to promulgate the message about the virtues of a career in engineering is before the age of 16. At 14, for instance, fewer children will have strongly held ideas as to their future careers. Even more important, they will not yet have committed themselves to some branch of intellectual endeavor (*e.g.*, Arts or Sciences) as the British system requires.

Those who have organized engineering taster courses appreciate the resources, and the time, that must be expended to operate them successfully. Insofar as engineering is about making things happen, about *doing*, it is difficult to convey this sense of achievement in leaflets or videos. It is relatively simple for a university department to produce 20,000 leaflets extolling the virtues of chemical engineering, but quite a different thing to actually enable 20,000 individuals to experience chemical engineering first hand.

No single department could hope to bring about significant changes on its own; instead, a concerted effort is required. In one sense, approaches to younger children should help eliminate some of the rivalry that exists between departments; recruitment by universities of students who attend their existing taster courses aimed at 16-year-olds is not insignificant. At 14, it could be argued, the objective becomes more one of gaining a convert to science and engineering as a whole. Also, at that early age it is unlikely that an individual would commit him or herself to any one

You are to carry out the synthesis of methyl salicylate. This is one of the active ingredents in the traditional remedy known as "Oil of Wintergreen." Methyl salicylate has a pattern of action similar to that of aspirin, i.e., cure for headaches and other general low-level aches and pains. Take 1 mol of salicylic acid (2-hydroxybenzoic acid) and react with 5 mol of methanol, using 0.2 mol concentrated sulfuric acid as a catalyst. The reaction should be carried out under reflux conditions (boiling of the mixture) for 5 hours. Extract the product into an equal amount of cyclohexane. Wash the organic phase with aqueous sodium carbonate solution and dry subsequently over anhydrous sodium sulfate. Distil to remove the cyclohexane and analyze your product.
The reaction scheme is given below:



What does the sulfuric acid do? Why do you use excess methanol: Why do you wash with sodium carbonate solution?
You will have to assemble your own apparatus from the glassware provided. This is a simple and safe synthesis to carry out provided that you adhere to normal safety procedures.

Figure 1. *Instructions for the laboratory synthesis of methyl salicylate.*

You are required to prepare an outline design and provide preliminary costing for an industrial facility to produce 300 tonnes per year of methyl salicylate. Methyl salicylate is produced by the reaction of salicylic acid and methanol in the presence of H_2SO_4 as follows:

$$C_6H_4.OH.COOH + CH_3.OH \xleftrightarrow{H_2SO_4\ (MW=98)} C_6H_4.OH.COO.CH_3 + H_2O$$

Salicylic acid	Methanol	Methyl salicylate	Water
MW=138	MW=32	MW=152	MW=18

The reaction takes 5 hours at the boiling point of the mixture. The methyl salicylate product separates out as an immiscible liquid layer, which subsequently has to be washed with dilute sodium hydroxide and then with water. To be cost effective, the industrial process operates somewhat differently from the laboratory scale experiment.
The facility will be operated as a batch process, but you are free to choose any operating pattern you consider suitable (e.g., 8 or 24 hours per day, 5 or 7 days per week, all year round campaigns, etc.). You may assume that sales demand is spread reasonably evenly over the year.
Your task
You will be split up into design teams for the purpose of this exercise and you are expected to elect one of your team members as team leader and s/he will be responsible for co-ordinating the teams' activities and for ensuring that a design is produced in time to make a brief presentation. For this, you will be issued with only two overhead transparency sheets. You should consider the following:

- *How you are going to make the reaction happen.*
- *How the plant is to be operated.*
- *The size and cost of your reactor (in m^3).*
- *How you will get the raw materials into the reactor.*
- *How you are going to avoid environmental pollution and what opportunities exist for recovery of raw materials.*
- *What other considerations would have to be taken into account in determining whether your plant will operate at a profit.*
- *Will this process yield a saleable product? If not, what additional steps need to be taken?*

Figure 2. *Design specification for a plant to produce methyl salicylate.*

particular department. We believe that the proposal described in this paper could form the basis of an initiative aimed at increasing awareness of engineering in these young people.

INITIATING LOUGHBOROUGH'S OUTREACH PROGRAM

We decided to try our recruitment scheme on 14-year-old children from a local school. We felt that this age group would have a sufficient knowledge of chemistry for the project and would be able to tackle what would be some quite novel concepts. Both we and their teachers felt the project should begin in an environment familiar to them—their own school laboratories. The proximity of the school to the university also meant that the children could continue to make use of school resources such as the libraries, internet access, etc. Involvement of a local school had other benefits; in particular, it was unnecessary to arrange accommodation and catering.

Involving the school's teachers was a key factor in the success and smooth running of the project. They were invited to the university about a week before the program was implemented and were fully briefed on logistic, safety, and other matters. They were given a brief overview of our laboratories (we intended that the school children would make use of them, as explained below). Overall supervisory and other duties were shared between two members of the academic staff of the department.

The students were asked to undertake laboratory synthesis of methyl salicylate. The instructions given to them are shown in Figure 1. We found it convenient to split the students up into teams of three or four, with each team being given one set of the necessary apparatus. The exercise proved to be well within their capabilities and was readily executed by the students over a two-day period.

The next stage of the exercise was for the students to design a facility for producing 300 tonnes per annum of methyl salicylate. This task was performed at the university. Before starting this part of the program, the students were reminded of the operations they had already conducted and which they would now have to "translate" to a larger scale. We achieved this by mimicking the operations using water in the place of methanol and sulphuric acid and sugar in the place of the salicylic acid. By removing the chemistry, the students were able to concentrate on the actual process of introducing the reactants into a vessel, heating them, mixing, cooling, etc. Although simple in concept, it proved highly effective. The design brief given to them is shown in Figure 2.

For this exercise we found it preferable to divide the students into teams of not more than six. Groups of this size helped break down the reserve felt by some individuals and to lead to lively discussions. It is essential to let the students generate ideas themselves, but it is equally important to have someone on hand to help them eliminate ideas that are evidently impractical, as well as to keep them on track generally. Both authors have personally carried out this role, and we have also made use of postgraduate demonstrators, who were carefully primed for the role with emphasis on the need to gently guide the students toward a solution.

TABLE 4
Program Timetable

Monday	Tuesday	Wednesday	Thursday	Friday
Introduction to the program — Introduction to chemical engineering	Laboratory synthesis	Introduction to the strategy of design — Group A labs Group B design	Group A labs Group B design	Design (both groups)
Lunch	Lunch	Lunch	Lunch	Lunch
The chemistry of salicylates	Visit to industrial analytical laboratory	Group A design Group B labs	Group A design Group B labs	Design presentations

The exercise can, to quite a large extent, be tailored to fit time constraints. We have operated it comfortably over a period of five days; two days in the chemistry laboratory and three at the university (see Table 4). In order to maintain high levels of enthusiasm among the students, we found it useful to intersperse this period of time with occasional forays into our teaching laboratories, where the students were first shown, and then allowed to operate, pumps, pneumatic solids conveying equipment, valves, heat exchangers, and other process plant equipment, Naturally, this was done under very closely supervised conditions. For this the children were divided into two groups, A and B, as shown in Table 4.

We feel it is essential that students obtain an overall process flowsheet relatively early in the exercise. It is also important to illustrate the depth of reasoning and the rigor that is required in the design of individual items of a chemical plant. We have tended to focus on the reactor as it is central to the process and therefore consideration of what happens both up and downstream of it needs to be taken into account.

Rather than overburdening the students with large collections of data sheets and the like, we have found it preferable to provide them with information as the need for it arose. For example, the students were required to make use of the library to determine what materials were suitable for fabricating the reactor. Another task, that of finding the bulk selling price of methyl salicylate, required them to make use of the internet. An advantage of this approach is that it does

not appear to the students as being over-prescriptive: as long as progress toward the final presentation is made, there is scope for exploring at least some of the "alleys and byways."

In the current generation of young people, it is perhaps not surprising to find the extent to which concern for the environment crept into a design exercise such as this. This actually presents an opportunity, which if seized can help the participants form a more balanced view about the chemical industry. It has been our experience that opinions held by most of the students on this subject tend to be negative ones; such views may not be well-informed, but they nevertheless represent ones that have to be confronted. The students themselves raised environmental concerns and were encouraged to see that solutions were available to meet those concerns. More importantly, they discovered this for themselves. We found that they acquired a rather proprietorial attitude—this was *their* plant and they were going to operate it in such a way as to cause minimum impact on the environment. Interestingly, no student has ever questioned the need for the plant; they seemed to recognize that such pharmaceutical products are of general benefit to humanity.

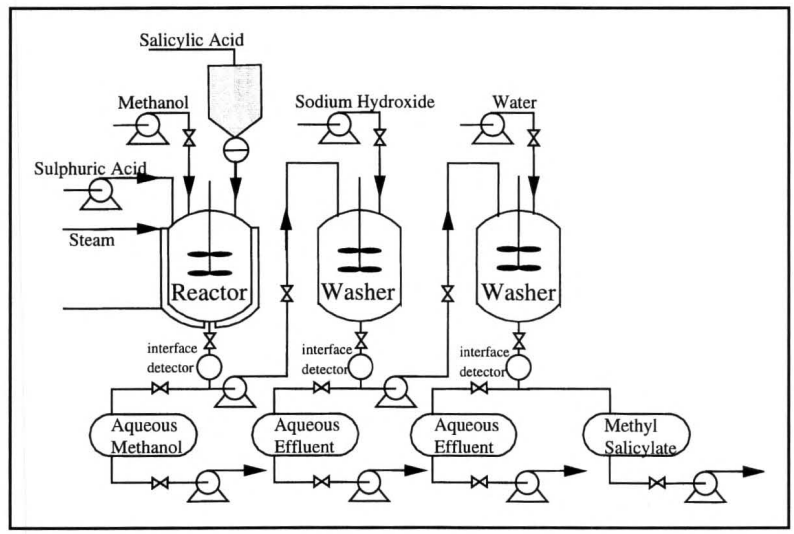


Figure 3. *Flow sheet for a methyl salicylate production facility.*

We stated earlier in this paper that the collaboration of industry was helpful in operating a scheme such as we have proposed here. We should note that this needs to be done with sensitivity. We have often been surprised at how alert young people are to what they consider to be overt forms of company propaganda. We wanted to ensure that the students primarily associated the whole exercise as a collaboration between their school and the university. We wanted to ensure that industrial involvement was less obtrusive, but was nonetheless significant to the success of the scheme.

In our case, this consideration took the form of a link with a local pharmaceutical company that undertook to conduct chemical analyses of the reaction products that the students had synthesized. The students were invited to the company laboratories and given a brief tour. They were then given a brief survey of potentially suitable analytical techniques followed by a fuller explanation of the process (High Pressure Liquid Chromatography, HPLC) actually used for their samples.

In order to make the design exercise as realistic as possible, a number of our industrial contacts agreed to receive telephone inquiries from the students concerning the costs of shift labor. There are a number of forms that industrial involvement could take, and those cited above represent typical examples only. The students' final task was to make a short presentation to an audience that included their peers. This in itself was a new experience for many of them, and it provided an opportunity to explain their processes and to present their principal findings.

We decided to prepare a process flowsheet (see Figure 3) to enable the students to see what one looked like and also to allow them to compare their designs to it. We wished also to introduce the concept that in engineering it is possible to generate more than one perfectly acceptable solution to the same problem.

CONCLUSIONS

We have operated this exercise for two successive years, in each case to groups of about twenty students. Feedback from both the students and their teachers has been extremely encouraging. It is justifiable to ask how the success of this scheme is to be assessed, but it is still too early to say if the initial enthusiasm expressed by the students will translate itself into more of them selecting the right combination of 'A' levels and ultimately electing to study chemical engineering, or indeed chemistry, at university. We view the operation of our scheme very much as a pilot exercise.

In any event, we are dealing with the statistics of small numbers, and as we have already stated, real benefits will only become apparent if the scheme is carried out on a significantly larger scale. The fact remains that all those who were involved in the program were unanimous in finding it a useful and enjoyable exercise. If it served no other purpose than to put the chemistry that these children receive at school into a context that is not normally available to them, then we have performed a useful service.

ACKNOWLEDGMENT

We wish to acknowledge the work of our colleague, Dr. Robin Wilcockson, in devising the design exercise that we adapted as part of our initiative. ❐

Project-Based, Spiral Curriculum

Continued from page 227.

courses. We were also interested in how it affects student attitudes and satisfaction about chemical engineering and their professional development within the discipline. External consultants were used to provide objective assessment through a variety of qualitative and quantitative measures. These included surveys, interviews, videotaping of class and project work, end-of-term course evaluations, a novel sophomore process-design competition, and an end-of-year comprehensive exam. The details and results of these assessment efforts will be described in Part 3 of this series of papers.

The following quotes from students on what they like most about the class after our first offering of the new curriculum support our belief that it was well received by students and that at least some of our objectives were met:

> *"...this cooperative learning thing through group projects has made this class one of the most thorough learning experineces of my life. I found it much easier to do assigned homework and do well on tests because of the thought processes established while working on a project."*

> *"...the ability to work in groups to solve problems. I really wasn't a big fan of group work because I could usually do just as well on my own. I've come to realize that groups can do so much more than an individual."*

> *"...without step-by-step procedures we were really forced to think and comprehend exactly what we were doing and why we were doing it."*

> *"...it taught all of us to use our heads first, then use the book. For the first time since coming to college, it felt as if I was learning to do something that would be very valuable to me in the future."*

ACKNOWLEDGMENTS

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EFFECTIVE COMMUNICATION FOR PROFESSIONAL ENGINEERING

Beyond Problem Sets and Lab Reports

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For the past three years, Georgia Tech's School of Chemical Engineering has offered a novel course for undergraduate students. It addresses topics in oral and written communication in the context of a bioengineering case study that simulates the variety of communications encountered in the modern workplace. "Effective Communication for Professional Engineering" features weekly guest speakers from a variety of professional disciplines, ranging from a practicing chemical engineer to an FDA regulator to a patent lawyer. This course is unlike traditional English courses, which are designed to generally broaden literary and composition horizons, and unlike traditional technical communication courses, which usually focus on lab reports and memos outside any "real-world" context.

The innovation of this particular course, which is subtitled "Beyond Problem Sets and Lab Reports," lies in its placement of student assignments in context with realistic professional settings. By bringing in a wealth of outside speakers and information, instructors encourage students to think in more creative ways to solve communication problems beyond the creation of a technically correct report. Students find themselves writing to a variety of audiences in more thoughtful ways, whether they are allaying the fears of a hypothetical public or persuading a corporate boardroom to adopt new technologies. They are required to draft a broad range of written and oral communication, including press releases, abstracts, patent disclosures, and speeches to a Board of Directors. Each new audience builds on a core of technical information common to the previous writing assignments, while lectures on audience analysis focus students on the thought processes involved in tailoring these various communications to different levels of technical understanding and informational need.

The pedagogical approach of this course also differs greatly from the relative anonymity of the larger lab or design class where technical communication is often addressed in chemical engineering curricula.[1,2] The students who sign up for this elective course continually experience a high level of peer and student-to-faculty interaction. Peer critiques of both written and oral presentations allow students to comment on each other's strengths and weaknesses. During the quarter, students are placed in shifting teams of two or three for activities that reinforce both the talks given by outside speakers and the instructors' lectures; these classroom interactions are then incorporated into the writing or speaking assignment due in the following class.

NEED FOR COURSE

Universities generally do well at teaching science and engineering students the fundamentals of their field. Our industrial colleagues tell us, however, that academia needs to do better at teaching students how to talk and write about technical topics to both fellow engineers and non-

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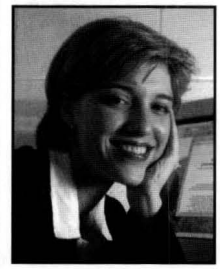


Melissa Bradley *is the Writing Program Specialist and Publications Coordinator of the School of Chemical Engineering at Georgia Tech. She has a BA in English from the University of Georgia and is currently pursuing her Master's degree in Information Design and Technology. She has freelanced as a technical and feature writer for a number of companies and magazines.*

engineers.[3,4] This course addresses that need in a real and practical way.

Although self-contained, this course also conforms to the broader curricular goals of the department, which include a writing and speaking program within the required unit-operations lab course. The writing aspect of the lab course, however, usually focuses on the technical and written skills necessary to produce just one form of communication—the technical report. And although these technical reporting skills are critical to an engineer's education, by no means will his or her future career as a professional be limited to communicating in only one format or to only one audience type.[5-7] Clearly, a range of communication issues, audience types, and writing and speaking formats should be presented in the undergraduate curriculum to prepare students for their roles as active participants at all levels of the engineering community.

Other communication courses offered outside of engineering are available, but generally have a weak connection with science as practiced in industry.[8] Moreover, we feel that the textbook-driven nature of most technical writing courses, with an emphasis on writing memos and lab reports, does not fully describe the diversity of form and content prevalent in inter- and intra-industrial communication. In contrast, our course provides a broad scope of communication issues and audiences, is based on a case study in context, and is linked to the real experiences of working professionals in the field.

COURSE GOALS

To give students widely applicable tools for written and oral communication, we have emphasized audience analysis and critical thinking[9,10] rather than conforming students to a series of prescribed formats. The goals of the course are to

1. *Provide students with the opportunity to write and speak to a diversity of audiences on at least a weekly basis.*
2. *Bring in outside professionals who work either in or with the engineering industry to discuss what they do and how they communicate.*
3. *Simulate the world of professional engineering by relating oral and written assignments to a common case study.*
4. *Focus on audience analysis as the basic building block of communication.*
5. *Integrate group projects with individual projects to acclimate students to working with others as a team.*[11]

COURSE IMPLEMENTATION

The integrated approach of this course, which seeks to simulate the "life of a professional engineer," is highlighted by extensive in-class discussion with outside professionals, as summarized in the ten-week course outline shown in Table 1.

The course starts by introducing students to technical aspects of our bioengineering case study, based on the Nicoderm transdermal nicotine patch developed by the Alza Corporation.[12,13] During the first two weeks, while digesting this technical information, students write a series of short reports on a current technical topic of broad interest, using information easily found on the Internet (*e.g.*, we used Viagra this year and the ValuJet crash last year). These reports are not formally graded, but are critiqued to help students start thinking about the effective communication of technical information to a variety of audiences.

Once the bioengineering case study begins in earnest, students are required to prepare a written and/or oral assignment every week (see syllabus excerpts in Table 2 and a sample assignment in Figure 1). Each written assignment is turned in to the instructors as well as to an anonymous classmate for peer critique.[14] The oral assignments are followed by immediate feedback from the instructor and from students (additional student self-assessment using a video tape of the presenta-

TABLE 1
Course Overview

Week 1	To set the stage for our case study, you are hired to develop a transdermal drug delivery system to safely and effectively administer nicotine across the skin.
Week 2	To learn first-hand about our case study, we will meet a **bioengineer from industry** who actually developed the first transdermal nicotine patch.
Week 3	Congratulations! You have invented a new transdermal delivery system. We meet with a **patent lawyer** and prepare an invention disclosure.
Week 4	Patent protection allows you to talk publicly about your work. We have a discussion with the **editor of a scientific journal,** prepare an abstract, and present a scientific talk.
Week 5	Your presentation was a great success and has attracted a lot of attention. We talk with a **science journalist from the popular press,** write a press release, and give a short presentation to concerned citizens.
Week 6	Now that you have figured out how to deliver the drug according to federal guidelines, we speak with a **government regulator** and prepare a brief for the FDA.
Week 7	Manufacturing your new device involves difficult procedures that the plant workers dislike. We meet with a **business manager** and prepare a memo for disgruntled employees.
Week 8	To bolster public support for the company based on your life-saving invention, we talk with a **graphic designer** and create an advertising campaign.
Week 9	You develop a second-generation technology that is more effective, but costs more to make. To convince your superiors to invest in this technology, we speak with a **corporate CEO** and prepare a talk for the Board of Directors.
Week 10	Your success has led to new job possibilities. We meet with a **career counselor** and a **professional interviewer,** prepare a resume, and have a mock job interview.

tion would also be helpful, but is not something we have yet implemented). By getting feedback from their peers as well as their instructors, students can simulate the roundtable discussions of teams in the workplace and implement suggestions for the next assignment.

While lectures by the instructors provide general lessons on communication relevant to the topic at hand, each guest speaker gives a detailed look at the requirements of his or her job and the communication issues arising from that job. Follow-up assignments permit students to put lessons from both lectures into practice.

KEY FEATURES OF THE COURSE

A number of features of this course distinguish it from other engineering and writing courses and have been critical to the course's success. Many of these features are not by themselves new, but their combination provides a novel approach to integrating concepts often missed in a conventional engineering curriculum.

- ***Academic, Industry, and Community Involvement*** Lectures are given not only by an engineer (Prausnitz) and a writing specialist (Bradley), but also by industry professionals who visit the class on a weekly basis. Moreover, we have involved newspaper journalism students from a local high school to attend some lectures and critique our students' press releases and oral presentations.
- ***Case-Study Format*** By following a single case study through the whole course, students have a sense of continuity and can focus on communication issues without having to learn new technical information each week. This approach also simulates the long-term development of projects found in industry.
- ***"Real-World" Context*** This course is as much about introducing students to the broad scope of life as a professional engineer as it is about communication. This helps students understand why good communication needs to be an integral part of their professional careers.
- ***Frequent, Short Writing and Speaking Assignments*** To build student confidence in communicating effectively, written or oral assignments are due in almost every class. Most assignments are short: 1000 words written or 4 minutes spoken.
- ***Emphasis on Audience Analysis*** Assignments and classroom discussion emphasize selection of content and format tailored to the intended audience to achieve the

TABLE 2
Syllabus Excerpts

Week 3: Communicating with Lawyers

Guest Speakers
Patrea Pabst, Arnall, Gregory, and Golden
Stephen Dorvee, Arnall, Gregory, and Golden

Assignment
Invention disclosure (see Figure 1)

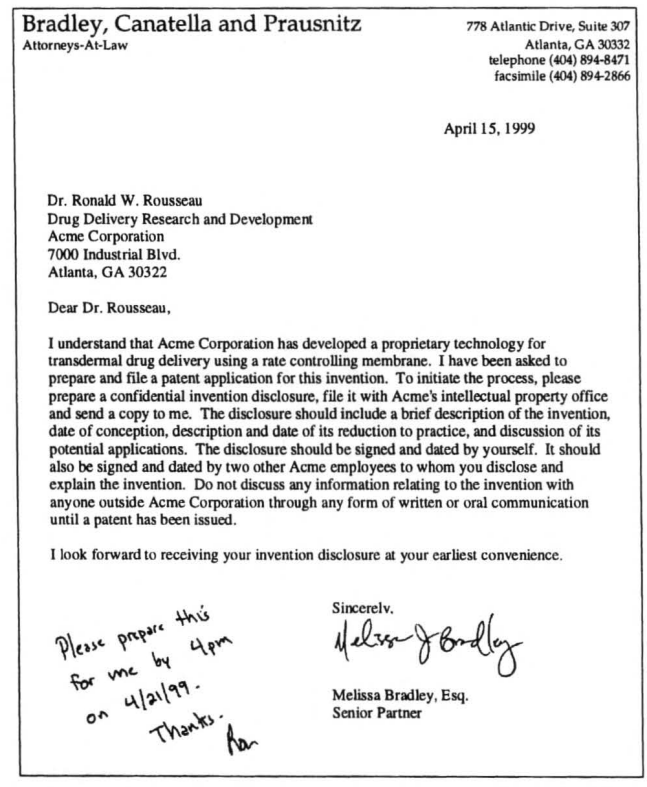
Reading Materials
- "Patents: What, Why, and How," M.H. Heines, *Chem. Eng. Prog.*, pp. 79-85, July (1992)
- *Do's and Don'ts for Keeping Lab Notebooks,* Fish & Richardson, P.C., Boston, MA
- "Copyright and Permissions," B.F. Polansky, in *The ACS Style Guide,* J.S. Dodd, ed., American Chemical Society, Washington, DC, pp. 137-143 (1986)
- "Subsaturated Nicotine Transdermal Therapeutic System," J.L. Osborne, et al., U.S. Patent No. 5,364,630 (1994)
- *Material Evaluation Agreement,* Georgia Tech Research Corporation, Atlanta, GA
- *Proprietary Information Agreement,* Georgia Tech Research Corporation, Atlanta, GA
- *Product Development and Commercialization Agreement,* ALZA Corporation, Palo Alto, CA

Week 5: Communicating with the Public

Guest Speakers (Only one speaker per course offering)
Ann Kellan, CNN
James Pilcher, Associated Press
David Jarmul, Howard Hughes Medical Institute

Assignments
Press release
Presentation at community meeting

Reading Materials
- *Communicating Science News: A Guide for Public Information Officers, Scientists, and Physicians,* The National Association of Science Writers, Greenlawn, NY
- *Headline News, Science Views II,* David Jarmul, ed., National Research Council, Washington, DC
- "Marion Merrell Dow Inc. Introduces First Nicotine Patch for Smoking Cessation," press release from Marion Merrell Dow, Kansas City, MO, Nov. 8 (1991)
- "Heart Attacks Reported in Patch Users Still Smoking," S.L. Hwang and M. Waldholz, *The Wall Street Journal,* p. B1, June 19 (1992)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April 15, 1999

Dr. Ronald W. Rousseau
Drug Delivery Research and Development
Acme Corporation
7000 Industrial Blvd.
Atlanta, GA 30322

Dear Dr. Rousseau,

I understand that Acme Corporation has developed a proprietary technology for transdermal drug delivery using a rate controlling membrane. I have been asked to prepare and file a patent application for this invention. To initiate the process, please prepare a confidential invention disclosure, file it with Acme's intellectual property office and send a copy to me. The disclosure should include a brief description of the invention, date of conception, description and date of its reduction to practice, and discussion of its potential applications. The disclosure should be signed and dated by yourself. It should also be signed and dated by two other Acme employees to whom you disclose and explain the invention. Do not discuss any information relating to the invention with anyone outside Acme Corporation through any form of written or oral communication until a patent has been issued.

I look forward to receiving your invention disclosure at your earliest convenience.

Please prepare this for me by 4pm on 4/21/99. Thanks. Ron

Sincerely,

Melissa J Bradley

Melissa Bradley, Esq.
Senior Partner

Figure 1. *Sample assignment for invention disclosure.*

desired effect rather than reiterating grammatical and generic stylistic rules already covered in freshman English courses.

- ***Instructor and Peer Critique of All Assignments*** All students receive written and oral feedback from both their instructors and their classroom peers on every written and oral assignment. Peer critiques are educational to the recipient as well as to the person offering the judgment.[14]

COURSE EVALUATION

The course's impact has been assessed by students in the course, guest speakers who visited the course, and the instructors. Results from Georgia Tech's standard anonymous student evaluation form, supplemented by a course-specific written evaluation, showed that students were very supportive of the course and strongly recommended it to others. Figure 2 shows responses to questions about overall effectiveness of the course. These responses suggest that the speakers, reading materials, and emphasis on written assignments were all well received. As indicated in the figure and in other comments, students felt a stronger emphasis on oral communication would be helpful, and following this suggestion, we will replace some of the written assignments with oral assignments in future course offerings. Also, the peer critiques were not perceived to be as useful as instructor feedback. To address this, we now require that peer critiques be at least a half-page long and that they identify specific problems and suggest concrete solutions.

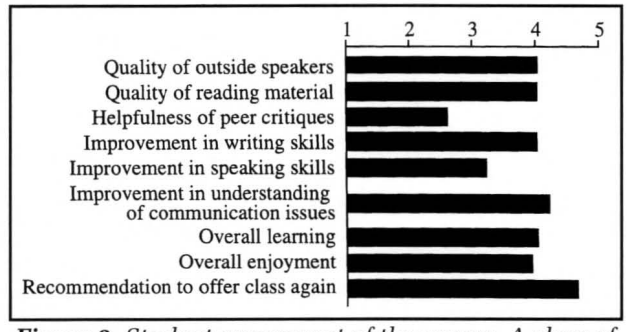

Figure 2. *Student assessment of the course. A class of 14 students was surveyed and asked to rate different aspects of the course on a scale of 1 (terrible) to 5 (excellent).*

Guest speakers have been uniformly supportive of the course and frequently commented that they wish they could have taken a similar course when they were students. All of them liked the guest-lecture format and found the approach relevant to their careers and their interactions with engineers.

As instructors, our assessment of the course is that it met the objectives we set out to achieve and has been beneficial to students, guests, and instructors alike. We believe that the guest speakers, who are coached in advance, have been critical to the course's success because they broaden the scope of the course and ensure its relevance to "real-world" issues. To maintain the sense of continuity necessary to the case-study course format, it was also important for us to continually clarify the connections between speakers, reading materials, and overall course objectives by providing follow-up presentations.

Despite the strongly positive reviews from students and guest speakers, it is difficult to get many students to sign up for the course in view of Georgia Tech curriculum requirements. Because this course cannot count toward any graduation requirement other than free elective credits (which most students do not need), the only students who have taken the course are those with enough interest and who are far enough ahead of the curriculum to fit it into their schedules. Thus, each course offering has attracted a small group (8 to 14) of strong, motivated students out of a chemical engineering graduating class of 120 to 150. In an attempt to expose a larger fraction of students to communication issues, we plan to offer the course on a 1-unit pass/fail basis (guest lectures only) in addition to the regular 3-unit graded option. We are also permitting graduate students to take the class and advertising the course more intensively outside of chemical engineering.

ACKNOWLEDGMENTS

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Random Thoughts . . .

THE ALUMNI SPEAK

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Several years ago I taught five chemical engineering courses in successive semesters to a cohort of students, beginning with the introductory course on material and energy balances (the stoichiometry course, CHE 205). I consistently used a variety of nontraditional instructional methods, most notably cooperative learning (assignments carried out by teams of three or four students with various measures being taken to assure individual accountability), and compared various learning outcomes for the students in these classes with the same outcomes for a group of traditionally-taught students. A description of the instructional methods and a summary of the results may be found in the *Journal of Engineering Education.**

In the fall of 1999, I sent a questionnaire to the 72 students in the study who graduated in chemical engineering, inviting them to reflect on their undergraduate education—what they liked and disliked, what helped prepare them for their current careers, and what advice they would have for today's beginning chemical engineering students. I eventually heard back from 50 of them, a respectable 69% return. Of the respondents—most of whom graduated in 1994 or 1995—33 (66%) were still involved in engineering and the remaining 17 were in different fields. Eleven (22%) had earned advanced professional degrees—four PhDs in chemical engineering, four medical degrees, and three law degrees. Those still in engineering included four process engineers, four environmental engineers, three each in engineering management, product development, production engineering, research and development, and quality assurance, nine in other engineering jobs, and one in graduate school. Those who left engineering included four computer systems managers or programmers, four physicians, three attorneys, two full-time homemakers, one executive recruiter, one human-resources manager, one machine operator, and one doctoral candidate in science and technology.

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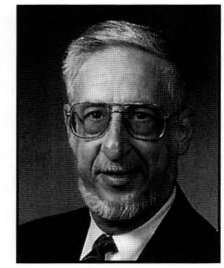

The respondents were asked to list the features of their undergraduate education that had proved to be most valuable in their career development. Items mentioned and the number of respondents citing them included

- *The problem-solving and time-management skills they acquired by working on so many long and difficult assignments (25)*
- *A variety of benefits gained from working in teams on homework (23)*
- *What they learned in the stoichiometry course (8)*
- *The broad knowledge base they acquired in the curriculum (6)*
- *Troubleshooting skills (3)*
- *Knowledge of statistics (3)*

No other item was mentioned by more than two individuals.

*(1) R.M. Felder, "A Longitudinal Study of Engineering Student Performance and Retention. IV. Instructional Methods and Student Responses to Them," *J. Engr. Education,* **84**(4), 361-367 (1995);
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Specific courses besides stoichiometry that were cited more than once included thermodynamics (2), mass transfer and separation processes (2), freshman chemistry (2), and mathematics (2).

In their open comments, almost every respondent spoke positively about group work, mentioning its learning benefits and/or the interactions with classmates that it fostered. For example, *"I formed very close relationships with my group members that remain today. I realized that I wasn't alone in struggling with new concepts and could garner support and help from teammates."* and *"Being forced to meet other students through required groupwork. . .kept me in the course long enough to develop the skills and self-confidence necessary to continue on in the CHE curriculum."* No one said anything negative about group work, although two respondents indicated that they disliked it initially and only later came to see its benefits.

Other features of the curriculum that got favorable citations from several students included

- The laboratory courses *("I always enjoyed the labs because you put to use all those hours of class time.")*
- In-class exercises *("The structure of the classes helped me to learn more by having active involvement in the class instead of the typical 'I lecture, you take notes and shut up' approach.")*
- Connections with chemical engineering practice *("Not only did Prof. ... try to provide real life examples, but we also had visitors from industry come in and explain how they used their college backgrounds in their fields. This information helped me to decide which industry was most appealing and best suited to my interests.")*

Common recommendations for beginning chemical engineering students were

- Pay attention to the stoichiometry course (10) *("CHE 205 is the most important course you can take—the first step in any engineering calculation is a material/energy balance.")*
- Study and work hard (9) *("Prepare yourself for a new way of thinking, 'cause this ain't high school, and you're not going to be able to coast. Work hard early and you won't have to play catch-up.")*
- Stick with it (8) *("Don't get discouraged if you don't do so well at first. People do get better as the curriculum progresses. (I did.)")*
- Take teamwork seriously (7) *("Get to know as many people in the class as soon as you can—this will get you through the homework and the tests. Teamwork is a way of life out in the real world. It will frequently be a major factor in how you are 'tested' at work.")*

Two students suggested that students struggling to make it through most of their chemical engineering courses might reconsider their choice of a career path. One put it this way: *"Any time you feel stubbornness getting you through some trial, you should consider why you need it. I fully believe that anybody will make passing marks in any subject area that truly interests him or her. If, on the other hand, you find the problems and concepts difficult, do not take this as a sign of intellectual failing, but rather as a sign of disinterest."*

Several points about the survey responses submitted by these alumni are particularly noteworthy. I was struck by the fact that only four respondents were involved in process engineering and three in engineering research and development, which is to say that fewer than one out of six were working in the areas addressed by essentially all of the core chemical engineering courses beyond the stoichiometry course. Many cited the value of the stoichiometry course in their academic and/or professional careers, stressing its importance in the advice they gave to beginning chemical engineering students, while no other core chemical engineering course was cited by more than two respondents. In contrast, almost every respondent noted the benefits of the problem-solving and teamwork skills they had acquired in the curriculum and many mentioned the value of their exposures to engineering practice. (The term "real world" came up fairly often.)

These observations suggest to me that the specific content of our core courses beyond stoichiometry may be less important than we tend to believe—much less important than the industrial relevance of what we teach and the extent to which we help our students develop problem-solving, communication, and teamwork skills. When we review and revise our curricula, we might do well to concentrate on addressing modern engineering practice beyond process design and analysis and on explicitly facilitating critical skill development, and worry less about how many advanced unit operations and differential equation solution techniques we can shoehorn into the courses. Besides helping our students, this change in focus won't do us a bit of harm at the next ABET visit. ❐

All of the *Random Thoughts* columns are now available on the World Wide Web at
http://www2.ncsu.edu/effective_teaching/ and at http://che.ufl.edu/~cee/

AUTOMOTIVE CATALYTIC REACTION ENGINEERING EXPERIMENT

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This experiment is an excellent combination of hands-on experiments, advanced analytical instrumentation, reactor modeling, and successful application of a numerical technique.

This experiment explores the area of heterogeneous catalysis using the automotive catalytic converter, which is the largest market for heterogeneous catalytic reactors. Since catalysts have been placed in approximately 225 million automobiles, nearly everyone with a car owns a catalytic converter. Students' interest in this experiment is piqued when they realize that their cars use this device every day. This immediate familiarity with the automobile allows students to approach the experiment with a confidence that helps them master the experiment's objectives.

A smaller, but growing, market for oxidation catalysts is in the destruction of volatile organic compounds from manufacturing sources. These catalytic reactors are designed using similar principles to the automotive catalysts. Base metals and platinum-group metals catalyze the CO oxidation and unburned hydrocarbons as well as reduce NO_x. Large installations have been in place on stationary internal combustion engines and gas turbines. For example, Johnson-Matthey has developed other products, such as CONCAT, for halogenated hydrocarbon destruction and Honeycat for standby generators and diesel engines working in confined spaces.

The automotive catalytic converter was originally introduced to reduce the photochemical smog problems in large cities such as Los Angeles and Tokyo. The automobile was identified as the major producer of smog precursors and a catalytic converter was required to rectify the problem. The standard catalytic converter consists of a honeycomb monolith support with a washcoat of metals on the surface of the support. A typical monolith is either ceramic or metal and consists of approximately 1-mm square channels 6 inches in length.

The current state-of-the-art catalyst is a three-way catalyst in which unburned hydrocarbons and CO are oxidized to CO_2 and H_2O, and NO is reduced to N_2. A brief review of these reactions and reactors has been presented by Schmidt.[1] Typical metals used in catalysis are platinum (Pt) and/or palladium (Pd) to oxidize CO and hydrocarbons, and rhodium (Rh) to reduce NO_x. Jacoby[2] reports that these catalysts are continually being engineered to reduce emissions from cars with cold engines and that they meet California's air standards of low and ultra-low emission vehicles. In all new catalysts, the reaction rate must be determined.

The temperatures that are used in the following experiment are above the 468°C autoignition temperature of propane. This presents an excellent vehicle for introducing safety concepts such as flammability limits and autoignition temperatures. At room temperature and atmospheric pressure, the flammability limits for propane are between 2.3 and 9.5 vol% in air. The concentration of propane we are using in this experiment is 2625 ppm, or 0.3% propane, and at these low concentrations it is difficult to burn a hydrocarbon.

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Dan Bosak *and* ***Luke Kline*** *are junior chemical engineering students at Rowan University. They have worked over the past two years as research assistants for the department and a National Science Foundation Undergraduate Faculty Enhancement Workshop. In addition to full-time studies, both are chemical operators on the weekends for the precious metal division of Johnson Matthey.*

Furthermore, the autoignition temperature is defined as the temperature at which spontaneous reaction occurs at stoichiometric propane and air concentrations (4% propane in air).

EXPERIMENTAL EQUIPMENT

Construction of this experiment is relatively simple; a small monolith is sealed inside a stainless steel tube, as shown in Figure 1. This yields a method for measuring gas flowrates, mixing the gases, and measuring the inlet and outlet concentrations.

The experiment can be performed with any catalyst that can oxidize a hydrocarbon, such as Pt or Pd. In this experiment, an actual automotive catalyst, donated by Johnson Matthey, was used. This catalyst can be fabricated using an aqueous Pt solution and buying the corderite monolith from Corning.[3] Alternatively, a used catalytic converter can be purchased from your local junkyard. If the junkyard catalyst has lost its activity, it can be regenerated using an acetic acid leaching process following the method of Angelidis and Papadakis.[4] A typical automotive catalyst has an ellipsoid cross section with axes of 5 5/8 and 3 inches. There are 400 square channels per in^2 having a length of 6 inches. To keep the reactor size small, you will need to cut a cylindrical section out of this monolith with a hacksaw and sand the section into a cylinder. A typical geometry for the cylindrical section has a diameter of 25 mm and a length of 30 mm.

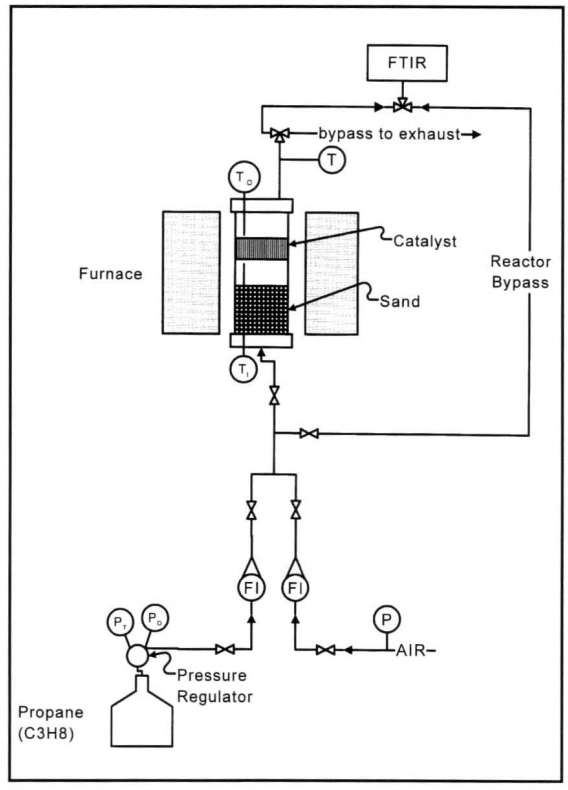

Figure 1. *Experimental catalytic reactor.*

To prevent gas from bypassing the catalyst, it is wrapped in a 3-mm-thick ceramic fiber blanket or felt. The monolith/felt combination should be carefully inserted into a 1 1/4" Schedule 80 (1.278" ID) 316 stainless steel pipe and gently pushed to 8 inches from the top of the 24" tube. The catalyst is held in place using the friction fit of the ceramic fiber gasket. A flow distributor and gas preheat zone is constructed from blank monoliths or a 6-in bed of washed sand is situated at the bottom of the reactor to both preheat and distribute the gas. The reactor temperature is maintained using a model F79345 Thermolyne split-tube furnace. The furnace has a 12-in heated zone and is rated for 2880 Watts and a maximum temperature of 1200°C. If your budget allows, you can purchase a 3-zone furnace to control the heat loss at the ends of the reactor tube.

The stainless steel tube can be sealed using machined end caps or the more expensive welded flange set. Thermocouples are placed through the top and bottom of the reactor. If threaded end caps are used, the thermocouple fitting must be placed exactly in the center of the tube so that the thermocouple can be inserted approximately 2 mm inside the monolith catalyst channel. The thermocouple end should be touching the channel walls to give the catalyst temperature. The second thermocouple inserted through the opposite end can either be placed in the upstream end of the monolith channel or be shielded and used to measure the entering gas temperature. The external diameter of these thermocouples is dependent on the width of an individual channel and is typically less than 1.16 in.

If a new catalyst is used it should be aged to give a nearly steady-state performance. The catalyst used in this experiment had palladium active sites and was aged at 900°C for 12 hours in 10% H_2O and balance nitrogen. The reaction rates of catalysts are typically reported on a mass, surface area, or active site basis. For commercial catalysts, either the mass or the external surface is known. For example, the catalyst used in this experiment has an average weight (monolith + metal washcoat) of 8.434 g.

Either propane or methane should be used as the hydrocarbon in this study. Propane, for this experiment, was obtained from MG Industries, has a purity of 99% propane, and is rated chemical pure (CP grade). Care must be taken to avoid any catalyst poisons and the standard barbecue propane tank would not be suitable since it contains sulfur compounds to warn the user of gas leaks. Air was obtained through the house compressor and regulated from 120 psig to 14 psig.

Since this experiment uses low concentrations of propane in air, the flowrates must be precisely controlled. The standard method is to use 2-stage regulators and rotameters. The air pressure was controlled using a ControlAir Inc High Precision 100-BA regulator. Propane can be controlled using a MG industries 2-stage regulator. A more user-friendly control scheme would be to use mass flow controllers at a cost of approximately $3,000 for two controllers and a control station.

For this experiment, gas concentrations can be analyzed using a number of analytical instruments, including gas chromatography, online flame ionization detectors, NDIR analyzers, or FTIR spectrometers. At Rowan, we are using a Nicolet Magna-IR® E.S.P. spectrometer. This spectrometer uses a 2-m gas cell path length with a KBr substrate beamsplitter. In this analysis the spectrometer can detect compounds that have a net dipole moment, such as CO_2 or NO, but cannot detect compounds such as O_2 and N_2, as shown in Figure 2. In the basic experiment presented in this paper, only the detection and quantification of propane is required. The complete Fourier Transform of a signal from a mixture of 1000 ppm of propane passed through a catalyst sample at a furnace temperature of 500°C is given in Figure 3. Propane is detected primarily from the C-H stretch in the range of 3000 to 2850 cm^{-1}. Figure 3 can be compared with standard spectra shown in Figure 2 to determine if other product gases are present.

The cost of the experimental apparatus, excluding analytical instrumentation, is approximately $5,000. If new analytical instrumentation is purchased, then the costs of an NDIR gas analyzer, gas chromatograph, or a Nicolet FTIR would cost approximately $7,000, $20,000, or $40,000.

LIGHT-OFF EXPERIMENTS

There are many experiments that can be performed with this reactor configuration, including

- *Examination of light-off curves*
- *Determination of reaction rates using integral-reactor method*
- *Determination of reaction rates using differential-reactor method*

In this paper the results of the light-off experiment will be presented since it is unique to the automotive catalyst industry. The experiment can be integrated easily in the first month of a reaction engineering course in which the basic mole balances for a plug flow reactor have been introduced to the student. It uses the concepts of conversion and the trade-off between the reaction rate and residence time in the reactor. In addition, this experiment can be conducted in approximately 1.5 hours and does not require high-precision quantification.

In cars with catalytic converters, the majority of pollutants are emitted from the car during the start-up period when the catalyst is cold and the required reactions are too slow. This is known in industry as the *cold-start* problem. Various strategies are being employed to eliminate this problem, such as electrically preheating the catalyst and adsorbing and storing the pollutants on a separate bed. The temperature required to activate the car catalyst is commonly referred to as the *light-off* temperature. At this temperature, the net heat released from the reactions is sufficient to maintain the catalyst at temperatures required to obtain high conversions. It is commonly thought that at temperatures below the light-off

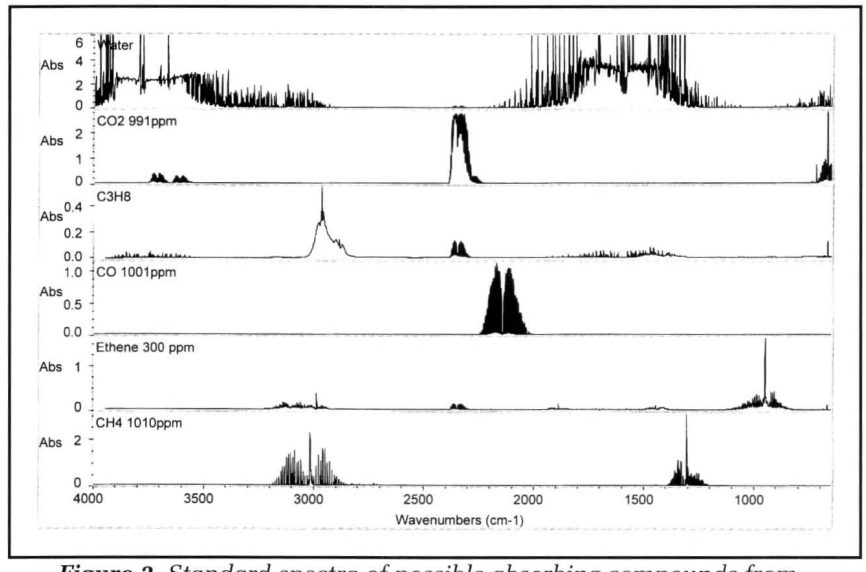

Figure 2. *Standard spectra of possible absorbing compounds from reactor outlet.*

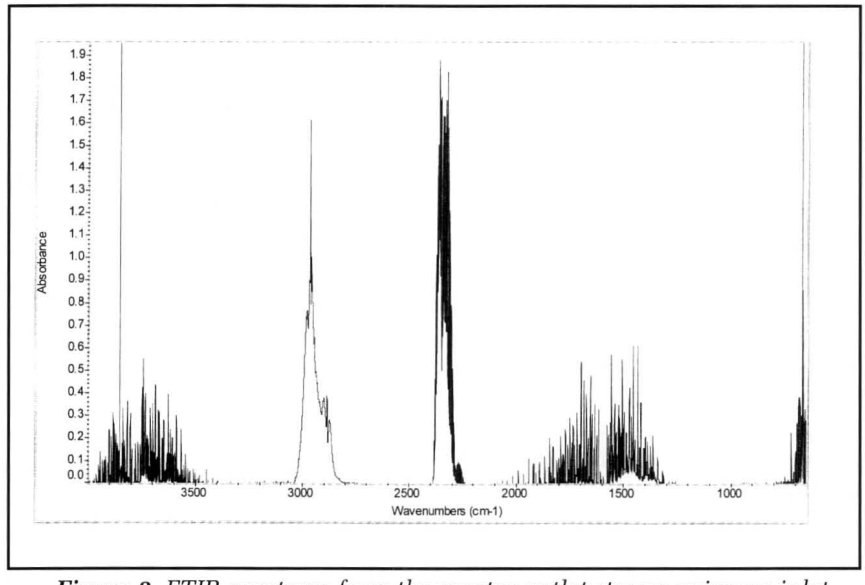

Figure 3. *FTIR spectrum from the reactor outlet stream using an inlet concentration of 1000 ppm propane in air at a furnace temperature of 500°C.*

temperature the catalyst is not removing pollutants, and at temperatures above the light-off temperature the catalyst is working. There are many definitions of the light-off temperature, but the most common is the temperature for which the conversion of a reactant reaches 50%.

Hayes and Kolaczkowski[3] show that this light-off temperature is a function of reactor size and reactor flowrate. This result should be obvious if you have just finished a reactor design course! Assuming a plug-flow model, the mole balance on propane is

$$\frac{dF_{C3H8}}{dW} = r \tag{1}$$

where F_{C3H8} is the molar flowrate of propane, W is the weight of catalyst, and r is the reaction rates with units mole propane/s/kgcat.

Assuming first-order kinetics and a constant flowrate, Q, through the reactor, Eq. (1) can be integrated to give

$$\chi_{C3H8} = 1 - \exp\left(-\frac{kW}{Q}\right) \tag{2}$$

Assuming an Arrhenius reaction rate constant and adjusting for the difference in rotameter flowrate and actual flowrate through the reactor gives

$$\chi_{C3H8} = 1 - \exp\left[-W\frac{A\exp(-E_a/RT)}{Q_0\frac{T}{T_0}}\right] \tag{3}$$

As the reactor temperature increases, both the reaction rate and conversion increase. At a given temperature, the conversion at high flowrates is less than the conversion at low flowrates. This clearly shows that the light-off temperature is dependent on the volume or geometry of the reactor and the flowrate of gases through the reactor.

The procedure for this experiment is relatively simple. The two flowrates chosen are of 14.5 and 7.76 L/min. The

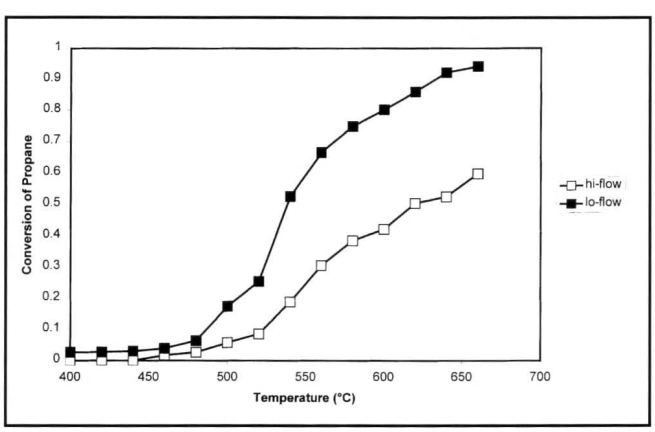

Figure 4. *Results of light-off determination experiment.*

Using this experiment, students are able to see the catalyst, to measure gas-phase concentrations and flowrates, and to model the reactor and find the reaction-rate parameters using a nonlinear regression of the data.

inlet concentration of propane in air is held constant at 2625 ppm. The furnace is initially set to a temperature of 550°C and the gas is analyzed at each flowrate. Next, the furnace temperature is increased by 25°C and samples are again taken at the above two flowrates. If the furnace temperature controller is programmable and an online analyzer is available, then the experiment can be automated following industry practice.

An example of the experimental results is shown in Figure 4. From these results the light-off temperatures at 50% conversion of propane are 620 and 538°C at 14.5 and 7.76 L/min, respectively. These distinctly different curves show that the outlet conversion of propane is a function of the flowrate through the monolith. This confirms that the light-off temperatures quoted in the literature can only be used to compare similar catalysts of equivalent geometry and gas flowrate. Students conducting these experiments will immediately see how they can use a simple reactor model to show the effect of flowrate on outlet conversion. The use of this experiment at an early stage in reactor design courses will help students learn basic concepts in reaction engineering.

DETERMINATION OF REACTION RATE PARAMETERS

A range of reaction rate expressions have been reported in the literature. Morooka, et al.,[5] reported the reaction rate for a palladium catalyst in an atmospheric flow reactor as nearly first order in propane:

$$r' = kC_{propane}^{1.3}C_{oxygen}^{-1.6}$$

with

$$k = 10^{6.89}\left(\frac{mol^{1.3}}{m_{cat}^2 m_{gas}^{0.9} s}\right)\exp\left(-\frac{151.8\,kJ/mol}{8.314\times10^{-3}\,kJ/(mol\,K)T}\right) \tag{4}$$

Recent reaction rate expressions for propane oxidation using commercial monolithic catalysts were reported as first order by Wanke[6] and Bennett, et al.[7] The pre-exponential and activation energy values reported for these first order rates are $A = 3.15\times10^4$ $m^3/(kg\ s)$ and $E_a = 89{,}126$ J/mol by Wanke and $A = 2.40\times10^5$ m/s and $E_a = 89{,}791$ J/mol by Bennett.

In order for the students to determine the reaction rate parameters, the reaction is assumed to be first order in pro-

pane concentration, which is in agreement with the results of the previous two investigators. Next, the students are asked to perform a nonlinear regression of the data using Eq. (3). With most packages, a good initial guess of the constants is required and an estimate is obtained using Eq. (2). Using a conversion of 0.52 and temperature of 813 K, the value of k is 0.0312. Next, a second value of k is determined and the values of A and E_a are calculated. An alternative method is to use the rate parameters given above as initial starting points. Finally, these values are used as the initial values for the regression of Eq. (3) with the data using the nonlinear regression package in POLYMATH.

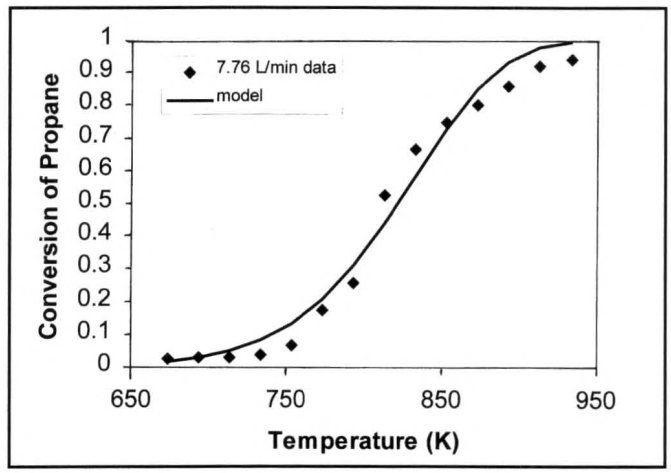

Figure 5. *Comparison of model with experimental light-off curve data.*

The results of a regression of the low flowrate data are shown in Figure 5. The reaction rate parameters from this fit are A = 4.81E+04 $m^3/(kg\ s)$ and E_a = 99,120 J/mol. This value of activation energy is very close to that of both Wanke and Bennett and is a reasonable activation energy. A fit using all of the data results in the reaction rate parameters of A = 2.39E+06 $m^3/(kg\ s)$ and E_a = 124,500 J/mol. This value of activation energy is higher than the values reported by Wanke and Bennett and below the values reported by Mooroka. This discrepancy in the activation energy could be related to a poor flowrate measurement using a rotameter (2% of full scale). Another possibility is that the catalyst reaction rate deviates from first-order kinetics.

This fit of the data with a reactor model enhances the student's connection between the concrete and the abstract. Students perform this simple experiment and observe the peak heights decrease as a function of furnace temperature and increasing flowrate. The peak area is related to the concentration of propane and a conversion is calculated. Finally, the students apply a reactor model to successfully describe the data. This experiment is an excellent combination of hands-on experiments, advanced analytical instrumentation, reactor modeling, and successful application of a numerical technique.

TRADITIONAL REACTION RATE DETERMINATIONS USING DIFFERENTIAL AND INTEGRAL REACTOR MODELS

There are many other experiments that can be performed using this equipment. The most basic in reaction engineering is the integral and the differential reaction-rate determinations. In the differential reaction-rate determination, the total conversion must be kept lower than 15% to obtain good results for an automotive catalyst.[7] In addition, the analytical technique for gas measurement must achieve a resolution of 1%. For the integral reactor, additional catalyst monoliths may need to be added. Using this apparatus, new catalysts can be tested and the experiment can be varied from year to year to minimize copying. Alternatively, a new hydrocarbon could be examined.

The major drawback of the above two reaction rate determinations is that they are time intensive; they require a large number of trials to obtain a reaction rate as a function of temperature. We have found the students quickly grow disinterested in this experiment when they conduct a large number of trials. The light-off experiments are simple since only one inlet concentration is used and the temperature can be ramped automatically.

SAFETY AND ENVIRONMENTAL CONSIDERATIONS

This experiment must be operated in a safe and environmentally responsible manner. All vessels must be rated for pressures greater than the release pressure of the liquefied propane tank. The concentrations of propane in the air stream are representative of hydrocarbons present in the exhaust gases and are well below the flammability limit of 2 mol%. The products of this oxidation are primarily CO_2 and water, which are not harmful and can be vented to an exhaust system. The furnace outlet is hot and students must be prevented from touching it.

CONCLUSION

These experiments have been run by Rowan engineering students and chemical engineering faculty at a unique hands-on industrially integrated NSF workshop on Novel Process Science and Engineering conducted at Rowan University. We believe that reaction engineering comes alive when students conduct innovative experiments in a laboratory setting. In addition, these experiments catch the students' interest because they are related to a commercially important process—the automotive catalytic converter. Using this experiment, students are able to see the catalyst, to measure gas-phase concentrations and flowrates, and to model the reactor and find the reaction-rate parameters using a nonlinear regression of the data.

ACKNOWLEDGMENTS

Special thanks to Chris Bennett, George Quinlan, and Wendy Manning from Johnson Matthey Catalytic Systems Division for donating pretreated catalyst samples and giving advice on reactor fabrication and catalyst operating conditions. Support for the development of this experiment was provided by a grant (DUE-9752789) from the National Science Foundation through the Division for Undergraduate Education and Rowan University.

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ChE letter to the editor

Dear Sirs,

We welcome the comments of Baird and Rama Rao[1] on our paper concerning a simple experiment on two-phase film flow[2] and hope that this discussion attracts the readers to this somewhat neglected area in lab courses of fluid mechanics.

Baird and Rama Rao point out that the experiment we described must be performed in tubes with internal diameter greater than 15 mm, for otherwise the bubble velocity will not be given by the simple equation

$$U = 0.345(gD)^{0.5} \qquad (1)$$

It is true that for smaller diameters the effect of surface tension becomes important and Eq. (1) ceases to be valid (if the tube is small enough, the slug will not move as pointed out), but in our paper we also present a general analysis for laminar film flow that makes no use of Eq. (1) (see Eq. (7) in ref. 2). However, if smaller tubes are used, the analysis presented is only approximate since the curvature of the film can no longer be neglected, and Nusselt's analysis is no longer applicable. Figure 1 shows the correct film thickness (calculated for cylindrical film flow[3]) as a function of the approximate film thickness given by Nusselt's analysis (neglecting the film curvature). It can be seen that if the dimensionless film thickness is greater than about 0.2, the errors in film thickness become larger than 10%.

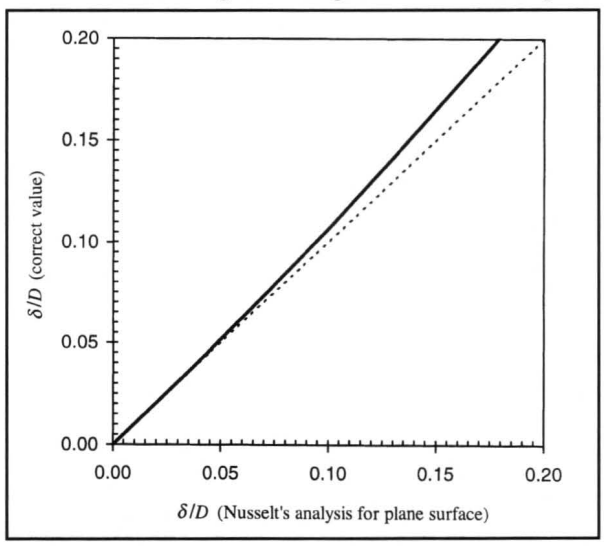

Figure 1- Correct versus approximate film thickness.

In order to minimize possible sources of error, it is suggested that columns with internal diameters in the range of 15-35 mm be used. With larger tube diameters it may be difficult to obtain laminar film flow, unless very viscous solutions are used. Also, one has to use longer columns due to greater velocities of the bubble, and the complexity of the instalation increases.

M.A. Alves, *Teaching Assistant*
A.M. Pinto, *Associate Professor*
J.R. Guedes de Carvalho, *Professor*
University of Porto, Portugal

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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 that elucidate difficult concepts. Manuscripts should not exceed ten double-spaced pages if possible and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

TUNING AND ACTIVATION OF A PI CONTROLLER DURING STARTUP OF A NON-ISOTHERMAL CSTR

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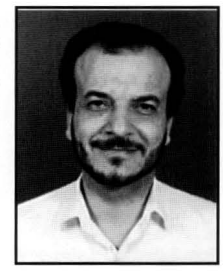
Continuous processes show dynamic behavior during start-up, shutdown, and when upsets occur during steady-state operation. Mathematical modeling, simulation, and control of these processes is relatively difficult because of the nonlinear nature of these processes and the activation and tuning difficulties of the controllers.

This paper applies proportional plus integral (PI) control to start up a non-isothermal CSTR. PI eliminates offsets and maintains an acceptable speed of response. Simple and straightforward schemes of activation are tried to start up the CSTR smoothly and to get the maximum attainable conversion. The importance of this control problem lies in the difficulty of triggering the controller and the retuning of the PI settings.

PROBLEM STATEMENT

We will consider the start-up of a non-isothermal CSTR, which has been studied in detail.[1,2] A reaction of the form $A + B \rightarrow C + D$ and of known kinetics has been considered. The CSTR has an overflow and two feed streams, one for pure A and the other for pure B. Mathematical models along with analytical and numerical solutions have been developed. Various types of start-up have been modeled and simulated, each type being represented by a different model. The models treated A and B as if they were in a total feed flow. In the present study, however, the models are modified to account for separate feed flows, because each feed flow is used here as a manipulated variable. Also, instead of using different models, the equations are grouped here in one general form:

$$\frac{dV}{dt} = F_1 + F_2 \text{ for } V < V_r, \text{ otherwise } \frac{dV}{dt} = 0 \qquad (1)$$



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$$\frac{dVC_A}{dt} = F_1C_{Af} - rV \quad (2)$$

$$\frac{dVC_B}{dt} = F_2C_{Bf} - rV \quad (3)$$

$$\frac{dVC_C}{dt} = (F_1 + F_2)(C_{Cf}) + rV \quad (4)$$

$$\frac{dVC_D}{dt} = (F_1 + F_2)(C_{Df}) + rV \quad (5)$$

$$V\left(\sum_{i=1}^{4} C_iC_{pi}\right)\frac{dT}{dt} = F_1C_{Af}C_{pA}(T_f - T) + F_2C_{Bf}C_{pB}(T_f - T) - rV\Delta H - Q \quad (6)$$

where

$$r = kC_AC_B \quad k = 10^{9.31}\exp\left(\frac{-48.32}{RT}\right) \quad Q = \frac{4V_r}{D}h_{air}(T - T_{amb})$$

The values of the parameters and the initial conditions are listed in Tables 1 and 2, respectively.

Required

1. Operating conditions during start-up have been found to affect the product quality. For example, changes in pressure drop in the head tanks produce changes in feed flows. Perform an open-loop simulation of the model and find the effect of changing the flow rate on the yield.

2. Operate the system starting from an empty tank with no inlet flows up to a fully filled tank with the maximum product concentration. Perform start-up once without disturbances and then with disturbances in the feed flows and in the input reactant concentration. Use a standard feedback PI control system, with the controlled variable being the concentration of product C.

TABLE 1
Process Parameters

Parameter	*Value*	*Parameter*	*Value*
Tf	24°C	Cp_A	75.25 J/mol°C
T_{amb}	29°C	Cp_B	175.3 J/mol°C
Vr	2.8 l	Cp_C	78.2 J/mol°C
h_{air}	2.5 J/m^{2}°C min	Cp_D	103.8 J/mol°C
ΔH	-1.5 kJ/mol	C_{Af}	0.1 mol/l
D	15 cm	C_{Bf}	0.1 mol/l
T_{ref}	24°C	C_{Cf}	0.0 mol/l
		C_{Df}	0.0 mol/l

TABLE 2
Initial and Starting Conditions

F_1	F_2	C_A	C_B	C_C	C_D	V	T
0.0 l/min	0.0 l/min	0.1 mol/l	0.1 mol/l	0.0 mol/l	0.0 mol/l	0.0 l	24°C

3. To perform start-up successfully, we need to tune and activate the controller. Use the modified Ziegler-Nichols[3] (Z-N) tuning method to find out the best settings, and then suggest different schemes to activate the controller.

SOLUTION

Simulation of the model equations (Eqs. 1-6) was performed using the package DASSL. This is a differential/algebraic system solver that uses the backward differentiation formulas of orders one through five. Figure 1 shows an open-loop simulation of the models for two different values of F_1 and F_2. As shown, a lower yield is obtained at a higher flow rate. Thus, the CSTR needs to be operated at lower flow rates. Specifically, $F_1 = F_2 = 0.1$ l/min, which produces $C_C = C_D = 0.0327$ mole/l, is considered as the desired operating condition (set point) in this work.

The manipulated variables are the positions of the valves, where the feedback control law[4] is given by

$$v_1(t) = v_{1o} + k_{c1}\left[C_C^{sp} - C_C(t)\right] + \frac{k_{c1}}{\tau_{11}}\int_0^t\left[C_C^{sp} - C_C(t)\right]dt \quad (7)$$

$$v_2(t) = v_{2o} + k_{c2}\left[C_C^{sp} - C_C(t)\right] + \frac{k_{c2}}{\tau_{12}}\int_0^t\left[C_C^{sp} - C_C(t)\right]dt \quad (8)$$

These laws will be implemented in a discrete time fashion with sampling time of 1 min. Note that these control loops form a split-range control scheme, because there are two manipulated variables to control one variable, with the control signal being split into equal parts, each affecting one valve. Although this is not the common split-range configuration, it simplifies the problem. Alternatively, v_2 can be driven by the error signal of C_D, which will result in the same

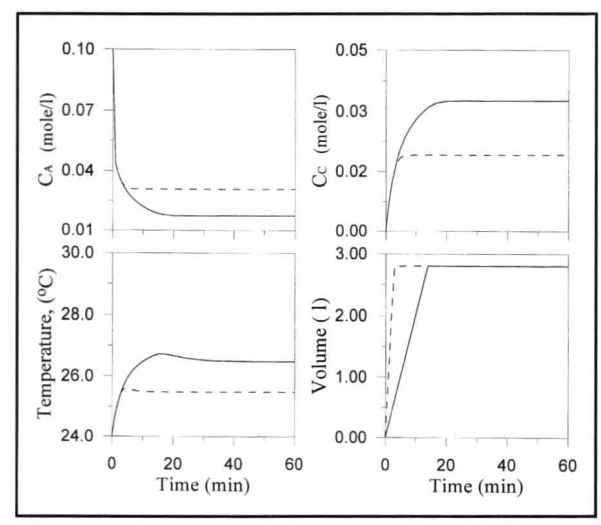

Figure 1. *Open-loop simulation: solid lines, $F_1 = F_2 = 0.1$ l/min; dashed lines, $F_1 = F_2 = 0.5$ l/min.*

control performance because the reaction has a constant stoichiometric ratio of one and identical valve dynamics. Note that feed flows are taken as linearly proportional to the valve positions of

$$F_1 = C_{v1} v_1 \tag{9}$$

$$F_2 = C_{v2} v_2 \tag{10}$$

Here, $C_{v1} = C_{v2} = 1.0$ mole/min.

Controller Tuning

Tuning determines the best settings for the adjustable parameters of a feedback controller. Closed-loop testing that produces constant output cycling is used in selecting these values. The desired values for k_{ci} and τ_1 are determined based on the modified Z-N tuning criterion. The original Z-N[5] method is based on the quarter decay ratio, which might result in oscillatory feedback response. The modified Z-N method gives more conservative settings. The purpose of the controller tuning is to obtain an initial value for the PI settings, which will be adapted on-line in a gain-scheduling formulation.

Tuning of the feedback control using an ultimate gain methods, *i.e.,* Z-N, is based on continuous incrementation of k_{ci} and observation of the resulting closed-loop response. The proportional gain that produces sustained oscillation is known as the ultimate gain from which the PI settings can be inferred.[6] Since the zero steady state is an unstable one, this method cannot be applied at this operating point. Thus, the PI settings are obtained by applying the Z-N as

$$k_{c1} = k_{c2} = -76.0$$

$$\tau_{I1} = \tau_{I2} = 1.0 \text{ min}$$

The negative controller gain is an indication of the reverse action mode, because the process has a negative static gain, k_p (see Figure 1).

Controller Activation

Consider Eqs. (7) and (8). In order to start up the reactor at t=0, the following condition must be satisfied:

$$v_i(0) = v_{io} + k_{ci}\left[C_C^{sp} - C(0)\right] > 0 \tag{11}$$

Obviously, this cannot be satisfied for a negative controller gain and a zero value of initial valve position. In order to overcome this problem, we examine four strategies of start-up:

Strategy I Perturb the inflows manually and trigger the PI algorithm simultaneously.

Strategy II Perturb the inflows manually and trigger the PI algorithm after a specific time interval.

Strategy III Trigger the PI algorithm with gain-scheduling according to $k_{ci}k_p$ = constant.

Strategy IV Trigger the PI algorithm with gain-scheduling using the IMC-type controller, $k_{ci}k_p = \tau/\lambda$

Notice that for Strategy 1, a large value of k_{ci} might cause v_i to remain zero for any value of v_{io} in its allowable range of [0,1]. The maximum allowable magnitude of k_{ci} in this case is $|k_{ci}| < v_{io} / C_C^{sp}$. Thus, a value of 0.1 for v_{io} and -2.0 for k_{ci} are used in Strategy I. As for Strategy II, the larger value of k_{ci} obtained by the Z-N method can be used with v_{io} =0.1 and the controller can be triggered one sampling time later.

In Strategy III, the controller gain will be adapted on-line according to $k_{ci}(t) = k_{co}k_{po}/k_p(t)$, where k_{co} and k_{po} are constant reference values. In this investigation, k_{co} is taken equal to -76, which is found by the Z-N method, and k_{po} as the static gain corresponding to $F_1 = F_2$ =0.1 l/min. Values of $k_p(t)$ can be estimated from Table 3, which lists different values for the static gain at various operating conditions. Values of k_p for F_1>0 were computed using the exact linearization of the process model and using the reaction-curve method. Both methods gave almost identical results. Initially, with F_1=0, the operation behaves like an integrator process; hence $k_p(0)$ was found by the pulse testing.[7]

For Strategy IV, the controller gain will also be adapted on-line with a changing process gain (k_p) and time constant (λ) according to $k_{ci} = \tau(t)/\left[\lambda k_p(t)\right]$ where λ is the IMC filter parameter or closed-loop time constant used to adjust the speed of the closed-loop response. Usually, an IMC-type tuning is used to determine fixed PI settings using identified process parameters. In addition, robustly tuned PI settings can be obtained by conducting an adequate robustness analysis.[8] Here, we allow the IMC-type controller gain to vary in order to adapt to the process changing gain.

The gain-scheduling approaches (Strategies III and IV) are conducted as follows:

- At t = 0

  set $k_p(0) = k_p(F_1=0)$ and $\tau(0) = \tau_{av}$

- At t > 0

  set $k_p(t) = k_{p,av}$ or interpolate k_p from the various values of k_p in the range $F_1 \in [0.01, 1.0]$

  set $\tau(t) = \tau_{av}$ or interpolate τ from the various values of τ in the range $F_1 \in [0.01, 1.0]$

RESULTS AND DISCUSSION

Start-Up Without Upsets

Closed-loop simulation for C_C^{sp}=0.0327 using the proposed activation strategies is depicted in Figure 2, which shows the time response of the product concentration, C_C, and the inlet flow of pure A, F_1. In all cases the controller was able to bring the product concentration to the desired

TABLE 3
Identified Process Gain and Time Constant at Various Operating Conditions

Step Change in F_1 (1/min)	τ (min)	Operating Condition	k_p
0.01	8	V=0	0.0111
0.05	6.5	V= 2.8, F_1 = 0.01	-0.1382
0.1	5	V = 2.8, F_1 = 0.1	-0.0338
0.2	3.5	V = 2.8, F_1 = 0.2	-0.02
0.4	2.5	V = 2.8, F_1 = 0.4	-0.0108
0.6	2.0	V = 2.8, F_1 = 0.6	-0.0071
0.8	1.5	V = 2.8, F_1 = 0.8	-0.0051
1.0	1.35	V = 2.8, F_1 = 1.0	-0.0039

value. The feed flows varied initially and then settled at their expected values of 0.1 1/min; however, the smooth response for Strategy II was only achieved by de-tuning the PI settings to $k_{c1} = k_{c2} = -9.1$, whereas the feedback response using the original values of the PI settings was found to be very aggressive.

It is clear from Figure 2 that Strategy I has the slowest response due to a small controller gain. A larger value of k_{ci} and consequently a faster response of Strategy I can be achieved using a larger initial perturbation value. With respect to the responses, Strategy III outperformed other strategies where the closed-loop response using a constant average value and a variable interpolated value of k_p are almost the same. Initially, F_1 varies for a few samples, then settles down to a constant value, giving a constant process gain. For strategy IV, the use of average values for the process parameters gave a smoother closed-loop. A value of λ = 2 produced a less aggressive performance, which took Strategy IV to a slightly slower response than that of Strategy III.

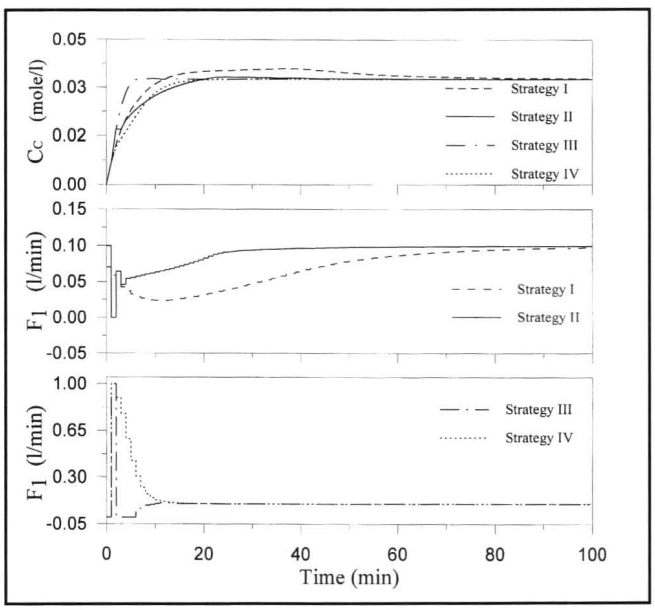

Figure 2. *Closed-loop response for* C_C^{sp} *=0.0327 mole/l.*

Start-Up with Upset in the Feed Flow

We next examine the change in the set point with a step of -0.05 in the feed flows at t=5 min during start-up (see Figure 3). The associated response of the valve openings is demonstrated in Figure 4. Obviously, the upset in the feed flows has marginal effect on feedback response of the product concentration for all cases except for Strategy I with $v_{io} = 0.1$, where a larger overshoot is observed. Unlike the previous case, the valve response differs from that of the feed flow since the disturbance affects the latter only. In this case, the

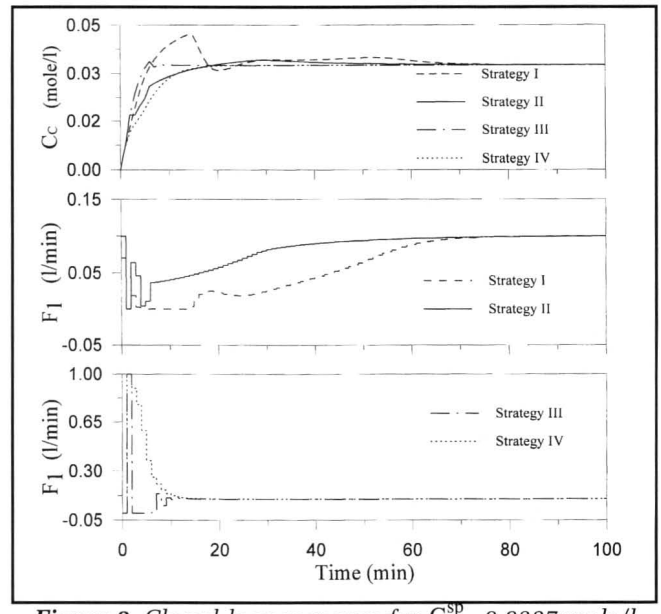

Figure 3. *Closed-loop response for* C_C^{sp} *=0.0327 mole/l with -0.05 step change in both feeds starting at t=5 min.*

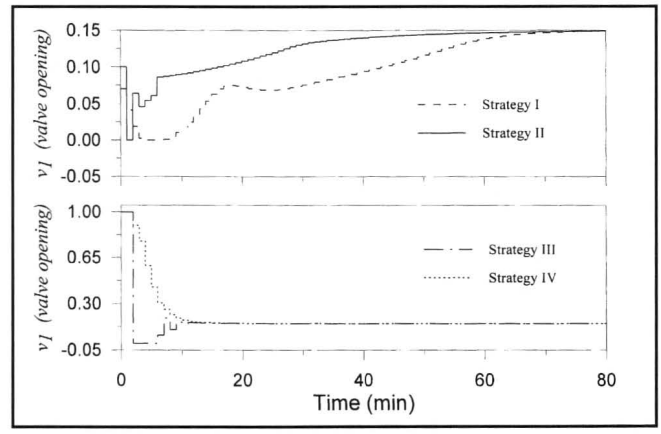

Figure 4. *Time response of valve position for* C_C^{sp} *=0.0327 mole/l with -0.05 step change in both feeds starting at t=5 min.*

valve position settles at a steady-state point higher than that in Figure 2. This increase in the valve opening was made by the controller to balance reduction in the feed flows produced by the disturbances.

Start-Up with Upset in the Feed Concentration

In order to illustrate the efficiency of the feedback control scheme, all of the control activation strategies were tested for the same set point as above, but with a disturbance in C_{Bf}. A step change of -0.02 mole/1 starting at t=10 min was considered (see Figure 5). Obviously, the proposed feedback schemes maintained the product quality at the desired value despite the sudden reduction in the inlet concentration, C_{Bf}. Ultimately, the inlet flows reached a value lower than that without upsets.

Start-Up with Different Set Point

Another advantage of the feedback scheme is its ability to maintain desired specifications without the knowledge of the optimal operating conditions beforehand. For example, in order to maximize the product yield, a larger set point for the product concentration can be specified for the controller. Figure 6(a,b), for example, illustrates the feedback response of the process for C_C^{sp}=0.04 mole/l. Although simulation indicates that such a yield is achievable, it operates the process at a very low throughput of 0.03 l/min. Similarly, Figure 6(c,d) demonstrates the process dynamic behavior for C_C^{sp} = 0.05 mole/l. Obviously, the reaction can be brought to such a high yield, but this would be at the expense of operating the process in a semi-batch mode as the feed flows approached zero at steady state.

CONCLUSIONS

Automatic start-up of a non-isothermal CSTR using a conventional PI control algorithm was considered. Four controller activation/adaptation schemes were tested and compared. Overall, Strategy III presented superior performance, full automation, and ease of implementation. Strategy I had the most sluggish response since the maximum allowable controller gain is restricted by the value of the initial valve opening. Strategy II lacks full automation and requires re-tuning for stability. On the other hand, Strategy IV requires proper adjustment of the IMC filter for good performance. Nevertheless, the performance of gain-scheduling approaches (Strategies III and IV) depends on the identified process parameters.

A theoretical model should be developed or identification methods be used along with these approaches. Another practical operation of the process is to maximize the yield and throughput. This issue can be addressed through implementation of optimal control

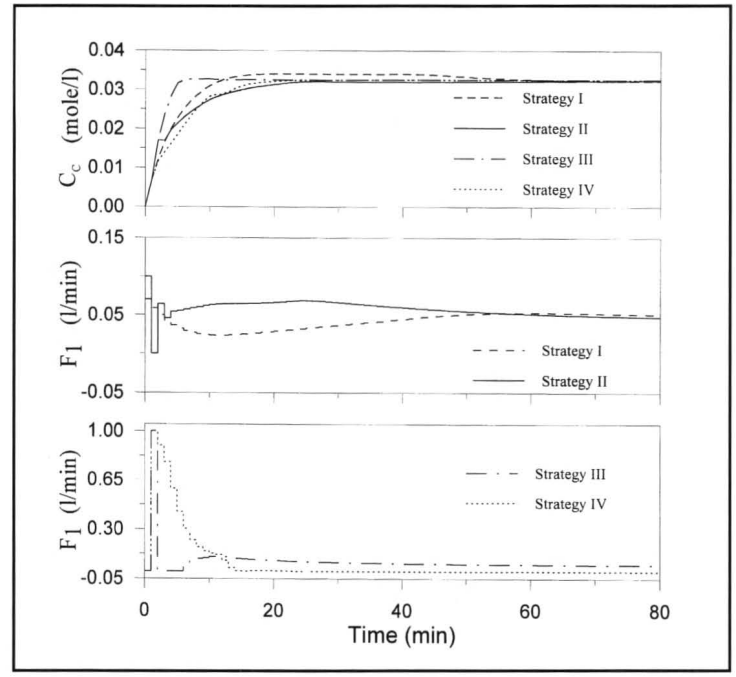

Figure 5. *Closed-loop response for C_C^{sp}=0.0327 mole/l with -0.02 step change in C_{Bf} starting at t=10 min.*

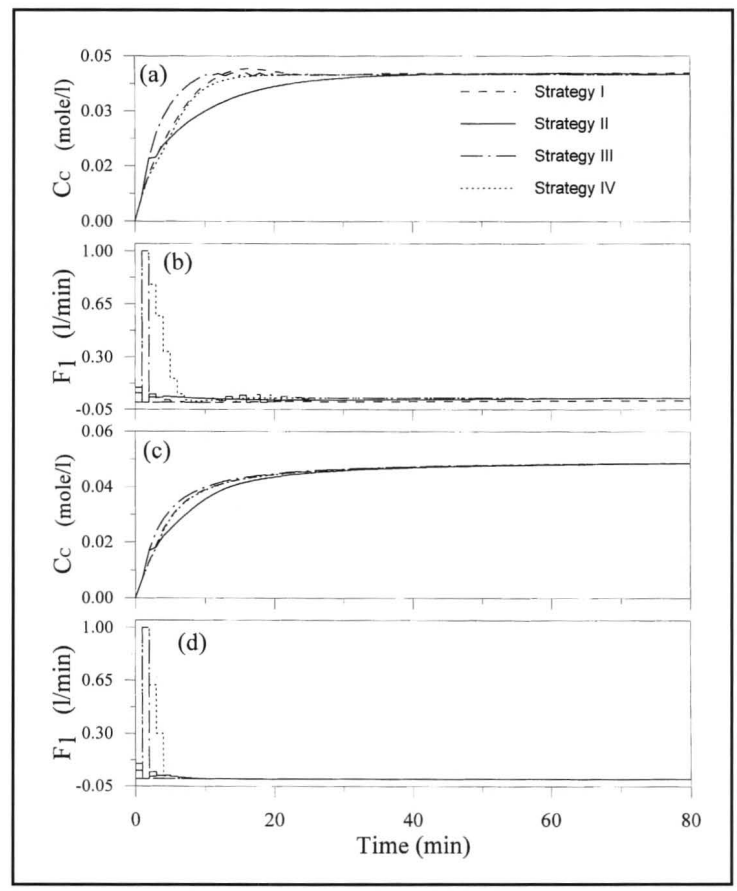

Figure 6. *Closed-loop response for C_C^{sp}=0.04 mole/l (a,b) and C_C^{sp} = 0.05 mole/l (c,d).*

theory.

Questions for Further Study

- ***Question #1:*** Derive the model equations considering one mode of start-up, *e.g.,* adding both reactants simultaneously, until the reactor overflows.
- ***Question #2:*** Consider an emergency shutdown in which the feed flows are suddenly stopped and the reactor is to be drained. Would the equations for this case be different from those representing start-up? How?
- ***Question #3:*** Repeat the above calculations using a first-order reaction.[9] Is it going to affect the controller settings and activation?
- ***Question #4:*** What would be the effect of adding a derivative action to the controller (*i.e.,* using a PID) on the start-up of the process?

NOMENCLATURE

C_i concentration of species i, mole/l
C_{if} feed concentration of species i, mole/l
C_i^{sp} concentration set point for species i, mole/l
C_{pi} heat capacity of species i, J/mole °C
C_{vi} characteristic constant for valve i
D reactor diameter, m
F_1 feed flow rate of pure component A, l/min
F_2 feed flow rate of pure component B, l/min
h_{air} heat transfer coefficient for air, kJ/m^2°C min
ΔH standard heat of reaction, kJ/mole
K reaction rate constant, l/mole min
k_{ci} controller gain for loop i
k_p process gain
k_p,av average process gain
Q rate of heat loss to the surrounding, kJ/min
r reaction rate, mole/l min
R gas constant, 0.008314 kJ/mole K
T reactor temperature, °C
T_{amb} ambient temperature, °C
T_f feed temperature, °C
T_{ref} reference temperature, °C
t time, min
V fluid volume, l
v_i valve i position
v_{io} initial position for valve i
V_r reactor volume, l
λ IMC filter (closed-loop time constant)
τ process time constant
τ_{av} average time constant
τ_I integral time for PI controller

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ChE *letter to the editor*

To the Editor:

In the Winter 2000 issue of *Chemical Engineering Education* there was an interesting paper by S.H. Munson-McGee[1] that presented a laboratory sequence with the objective of developing abilities in chemical engineering students according to EC 2000 criteria.[2] The author describes a four-course sequence, beginning with the study of the theoretical aspects of experimental design and data analysis and finishing with a unit operations laboratory.

Table 1 of that paper shows a short description of each of the nine experiments that can be carried out by the students with the Process Instrumentation Laboratory course. Unfortunately, the mentioned Table 1 contains a typographical mistake and the simple change of a "d" for a "b" causes a considerable conceptual effect: effectively, the experiment, titled "A*b*sorption by activated carbon. Blue food coloring was a*b*sorbed from aqueous solutions..." is actually an a*d*sorption experiment. (Table 2 refers, correctly, to this experiment as an a*d*sorption process.)

From my point of view, it is important to correct this type of typographical error where two very similar words refer to two very different processes, in order to prevent confusion and conceptual mistakes among students. This is especially important in journals such as *Chemical Engineering Education* because of its content, which is very readable by chemical engineering undergraduates.

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A TRAINING SIMULATOR FOR COMPUTER-AIDED PROCESS CONTROL EDUCATION

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Hands-on challenges that demonstrate and reinforce important concepts benefit the learning process—this is especially true for the often abstract subject of process dynamics and control. Hands-on challenges can be motivating, can promote critical thinking, facilitate understanding in the use and limitations of the theory, and help prepare students for the challenges of the professional world.

Too often the application of textbook theory is limited to solving questions listed at the end of the chapter. One typical question is to have the student expand or extend a mathematical development presented in the book. Another is to provide bits of data and challenge the student to select and employ a combination of formulas to obtain a desired result.

Unfortunately, even when cleverly crafted, these textbook problems fall short of providing students with the depth or breadth of practice required for comprehension and mastery.[1,2] Thus, the Chemical Engineering Department at the University of Connecticut supplements the textbook with laboratory exercises. Hands-on laboratory exercises are extremely important to learning because they help students make the intellectual transition from theory to practice.[3] The abstractions presented in textbooks are literally brought to life through the tactile nature of a lab experience.

Unfortunately, the reality of the laboratory at the University of Connecticut is that each study can take many hours, and even days, to perform. Also, equipment failures and other problems teach the important lesson that the real world can be uncertain (this lesson is not usually intended to be the objective of a particular assignment, however). Thus, students rarely explore more than a very few central concepts in the lab.

A training simulator offers an alluring method for providing students with the significant hands-on practice critical to learning process control. The proper tool can provide virtual experience much the way airplane and power-plant simulators do in those fields. It can give students a broad range of focused engineering applications of theory in an efficient, safe, and economical fashion. And it can work as an instructional companion as it provides interactive challenges that track along with classroom lectures.

Process control is a subject area well suited to exploit the benefits of a training simulator.[4] Modern control installations are computer based, so a video display is the natural window through which the subject is practiced. With color graphic animation and interactive challenges, a training simulator can offer experiences that literally rival those of the real world.[1] These experiences can be obtained risk free and at minimal cost, enabling students to feel comfortable exploring nonstandard solutions at their desks. If properly designed as a pedagogical tool with case studies organized to

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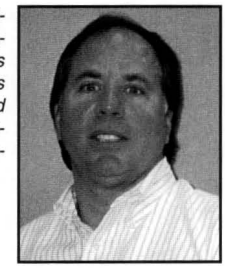

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present incremental challenges, we believe learning can be enormously enhanced for process control with such a training simulator.

A CHEMICAL PERSPECTIVE

Each discipline views process control from a different perspective. To help orient the reader, consider these "typical" examples drawn from chemical process control:

Process Variables: *temperature, pressure, pressure drop, level, flow, density, concentration*

Final Control Elements: *solenoid, valve, variable speed pump or compressor, heater or cooler*

Control Algorithms: *on/off, PID, cascade, ratio, feed forward, multivariable decoupler, model predictive*

Process Applications: *reactors, separators, distillation columns, heat exchangers, furnaces*

Many chemical engineering processes are literally one-of-a-kind. Consequently, their associated control system will be unique in design and implementation.

Additionally, chemical processes can be nonlinear and nonstationary, and can have long time constants, significant dead time, and/or noisy measurement signals. Disturbances occur from numerous sources, including loop interaction from other controllers in the plant.

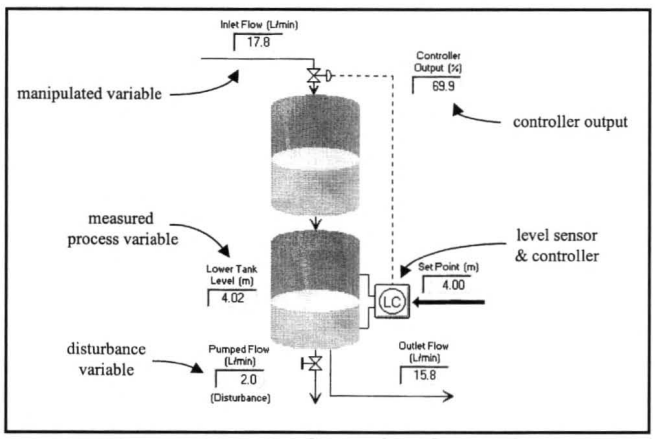

Figure 1. *Gravity-drained tanks graphic.*

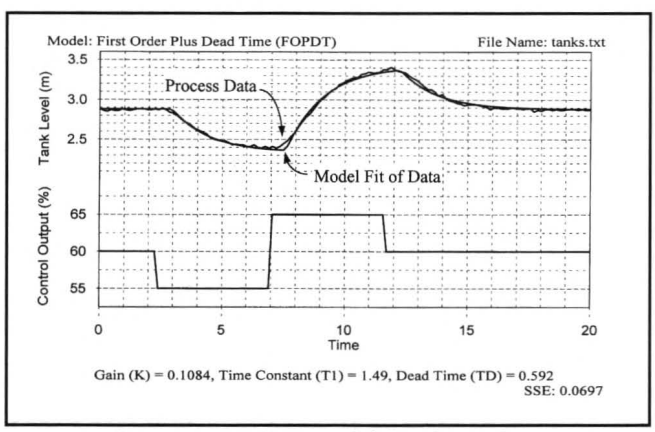

Figure 2. *FOPDT model fit of text data.*

EXAMPLE LESSONS

The following lessons have been drawn from the Control Station process control training simulator to illustrate the value such software provides the curriculum. We note that training simulators are distinguished here from tools such as Matlab,[5] which have a primary function of design, analysis, and simulation. The reader can download a free control-station demo at

<www.engr.uconn.edu/control/>

P-Only Controller Performance

The computer graphic display for the gravity-drained tanks process, shown in Figure 1, is two vessels stacked one above the other. Liquid drains freely through a hole in the bottom of each tank. The controller output signal manipulates the flow rate of liquid entering the top tank. The measured process variable is liquid level in the lower tank. The disturbance variable is a secondary flow out of the lower tank from a positive displacement pump, so it is independent of liquid level except when the tank is empty.

Students begin their studies with this process because its dynamic behavior is reasonably intuitive. If they increase the liquid flow rate into the top tank, the liquid levels rise in the tanks; if they decrease the flow rate, the levels fall.

The traditional place to begin a course is with the study of process dynamics. Students generate a step-test plot and compute by hand the first-order-plus-dead-time (FOPDT) model parameters: steady-state process gain, K_p, overall time constant, τ_p, and apparent dead time, θ_p. After they have gained mastery with hand calculations, they use tools that automate the model-fitting task so they can explore more practical tests. A Control Station fit of test data is shown in Figure 2 for the gravity-drained tanks.

Students use their FOPDT model parameters in tuning correlations to compute a P-Only controller gain, K_C. Figure 3 displays a Control Station strip chart showing set-point

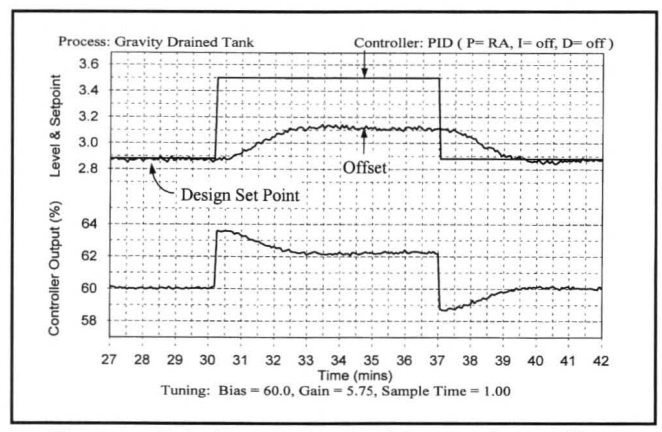

Figure 3. *P-Only set-point tracking results in offset.*

. . . we do not believe a training simulator is better than, or a replacement for, real lab experiences. In fact, we believe that hands-on studies with actual equipment are fundamental to the learning process.

tracking performance for the gravity-drained tanks under P-Only control. The K_C for the controller is computed from the integral time-weighted absolute error (ITAE) correlation,[6,7] using the FOPDT model parameters from Figure 2.

With this as a starting point, the students now turn to what-if studies. The investigation of Figure 4 explores how K_C impacts offset and oscillatory behavior for set-point tracking under P-Only control. Students also explore disturbance rejection under P-Only control. Is the best tuning for set-point tracking the same as for disturbance rejection? And, how is "best" tuning defined?

For this and all Control Station processes, the student can change the level of random noise in the measured process variable. They can also manipulate the controller output signal, set point, and disturbance variable using a step, oscillating, ramp, or pseudo-random binary-sequence (PRBS) signal sequence. The current version of Control Station offers only one disturbance variable for each process, and this disturbance can be changed at will by the student. We note that this is not realistic in that a real plant can have many disturbances from a variety of sources that will affect the process, and as disturbances, they are generally not available for manipulation by the engineer. The students are made aware of this during class.

PI Control and Nonlinear Behavior

The computer graphic for the countercurrent, shell and tube, lube oil cooler (a kind of heat exchanger) is shown in Figure 5. The controller-output signal manipulates the flow rate of cooling liquid on the shell side. The measured process variable is lube oil temperature exiting on the tube side.

Students learn an important lesson about process dynamics by studying the nonlinear character of this process as shown in Figure 6. The steady-state gain of the process

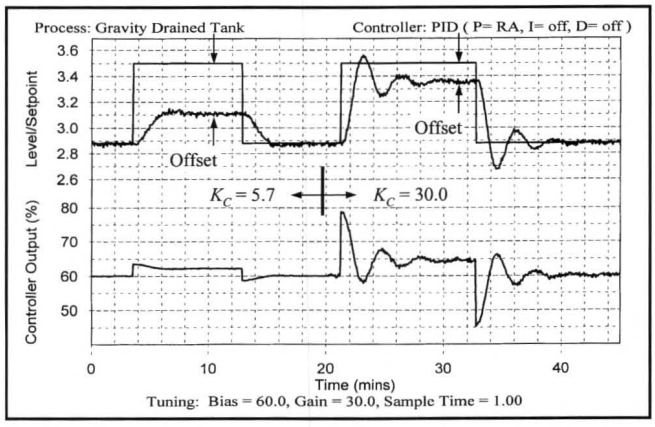

Figure 4. *P-Only performance changes as K_C changes.*

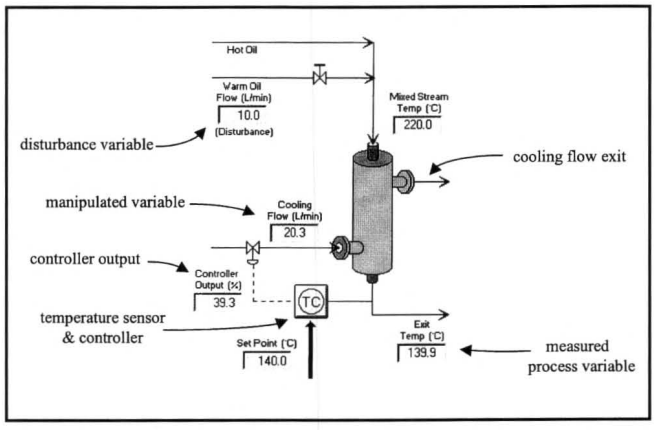

Figure 5. *Heat exchanger graphic.*

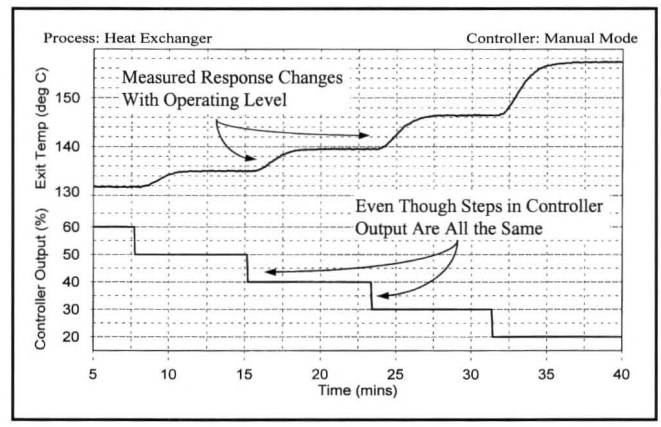

Figure 6. *Heat exchanger displays nonlinear behavior.*

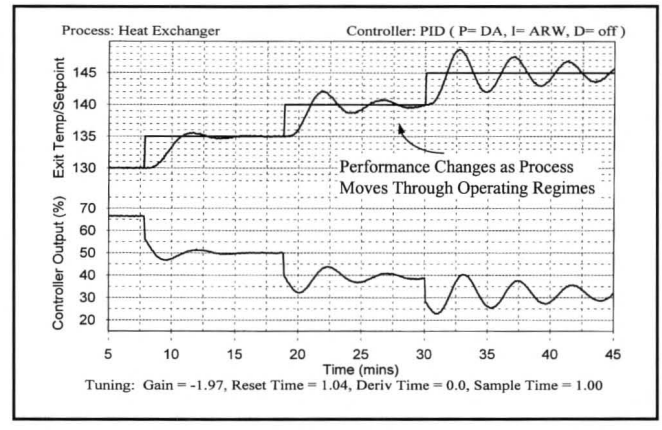

Figure 7. *Nonlinear behavior impacts performance.*

clearly changes as operating level changes. Less obvious is that the time constant of the process also changes.

For processes that have such a nonlinear character, the performance of a controller will change as the process moves across operating levels. Figure 7 illustrates this point. The exchanger is under PI control, and as the set point is stepped to different operating levels, the nonlinear behavior of the process clearly impacts set-point tracking performance. Thus, students learn that a controller is designed for a specific or design level of operation. Best practice is to collect dynamic test data as near as practical to this design.

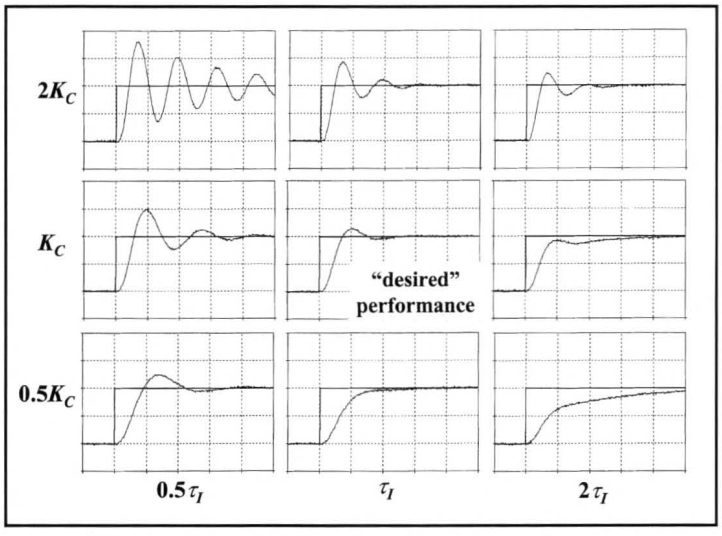

Figure 8. *PI controller tuning impacts performance.*

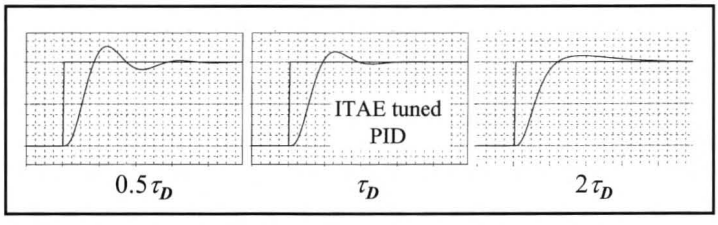

Figure 9. *Derivative action impacts oscillatory behavior.*

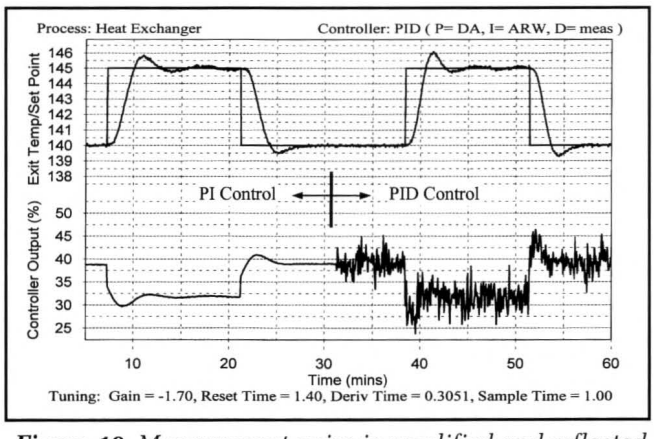

Figure 10. *Measurement noise is amplified and reflected in controller output signal.*

Figure 6 also shows that the heat exchanger has a negative steady-state gain. Students learn that a complete design includes specifying the action of the controller (reverse vs. direct acting).[6-8] They learn this concept because if they enter it wrong, the controller output will quickly drive the valve to either full open or full closed and it will remain there until the correct controller action is entered.

For what-if studies, students explore how PI controller tuning parameters interact and affect set-point tracking performance. Figure 8 shows a tuning map that they develop from an orderly tuning investigation using an ideal linear transfer function process available in Control Station.

PID Control and Measurement Noise

Derivative action can decrease the process settling time because it resists rapid movement in the measured process variable.[6] In Control Station, the PID controller algorithm is currently implemented using the ideal (noninteracting) form[6-9] with a choice of derivative action either on controller error or process measurement. Students learn how derivative action impacts controller performance with studies similar to that shown in Figure 9, which focuses on the derivative time tuning parameter.

The center plot of Figure 9 shows the set-point tracking performance of a PID controller tuned using the ITAE[6,7] for set-point tracking correlation. For all plots in Figure 9, K_C and τ_I remain constant and the measurement noise has been set to zero. The plot to the left in Figure 9 shows how the oscillating nature of the response increases as derivative action is cut in half. The plot to the right shows that when derivative action is too large, it inhibits rapid movement in the measure process variable, causing the rise time and settling time to lengthen.

When noise is added to the measured process variable, students learn that derivative action amplifies it and reflects it in the controller output signal. Figure 10 shows this quite clearly with a side-by-side comparison of a PI and PID controller. For this comparison, the same amount of measurement noise was used throughout the experiment. This study helps students visualize that a PI controller is not impacted by noise while the derivative action of the PID controller reflects and amplifies it in the controller output signal.

Students also compare derivative on controller error to derivative on process measurement. Watching the derivative on error "kick" after a set-point step is a more memorable experience than simply hearing about it.

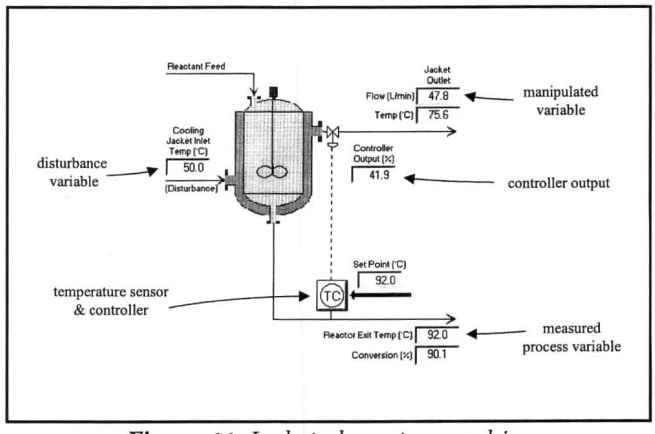

Figure 11. *Jacketed reactor graphic.*

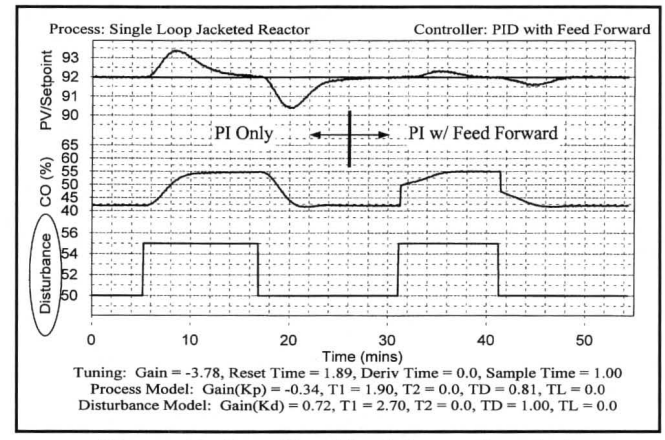

Figure 12. *Benefits of feed-forward control.*

Cascade, Feed Forward, and Disturbance Rejection

The jacketed reactor graphic, shown in Figure 11, is a continuously stirred tank reactor in which an irreversible exothermic reaction occurs. Residence time is constant in this perfectly mixed reactor, so the steady-state conversion from the reactor can be directly inferred from the temperature of the reactor product stream. To control reactor temperature, the vessel is enclosed with a jacket through which a coolant passes.

The controller output manipulates the coolant flow rate through the jacket. The measured process variable is product exit-stream temperature. If the exit-stream temperature is too high, the controller increases the coolant jacket flow to cool down the reactor. The disturbance variable is the inlet temperature of coolant entering the cooling jacket.

The jacketed reactor can be run in three configurations: feedback control, as shown in Figure 11, feed forward with feedback trim, and cascade control. When the cooling jacket inlet temperature changes, the ability to remove heat changes and the control system must compensate for this disturbance. Cascade and feed forward are control strategies used for improved disturbance rejection.

Cascade design involves the tuning of two controllers. Feed forward requires identification of an appropriate process and disturbance model.

The rejection of a step change in the disturbance variable (jacket inlet temperature) for a single loop PI controller is compared in Figure 12 to a PI with feed forward controller. The benefit of feed forward is clear for this process because for the same disturbance, the measured process variable has a much smaller maximum deviation and a faster settling time.

Students compare single-loop, feed-forward, and cascade control in a series of exercises. They investigate tuning issues, which PID modes to use in a cascade, the order and accuracy of the models needed for feed-forward design, plant-model mismatch, dead-time issues, and a host of other interesting challenges.

Control Loop Interaction and Decoupling

The graphic shown in Figure 13 is a binary distillation column based on the model of McCune and Gallier.[10] The column has two measured process variables and two manipulated variables. The reflux rate is used to control distil-

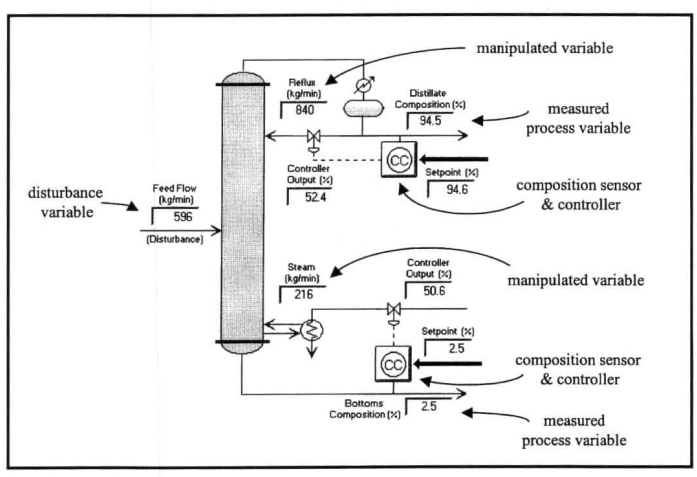

Figure 13. *Distillation column graphic.*

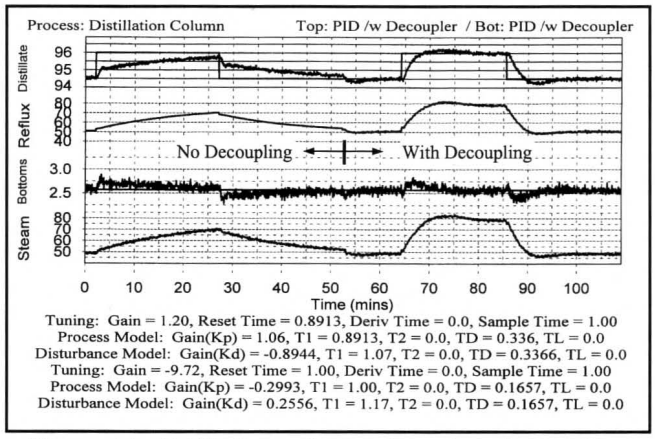

Figure 14. *Distillation column shows loop interaction.*

late purity and the steam rate is used to control purity of the bottoms stream.

Students use this process to explore the interactions that can occur in such multicontroller applications. Control-loop interaction occurs because when the distillate purity out of the top of the column is too low, the top controller compensates by increasing the flow of cold reflux into the column. This increased reflux flow will indeed cause an increase in the distillate purity. The additional cold reflux will work its way down the column trays, however, and eventually begin to cool the bottom of the column. This cooling causes the purity of the bottoms stream to move off set point and produce a controller error.

The bottom controller compensates by increasing the flow of steam into the reboiler. This produces an increase in hot vapors traveling up the column, which eventually causes the top of the column to begin to heat up. The result is that distillate purity again becomes too low. In response, the top controller compensates by again increasing the flow of cold reflux into the column.

This controller "fight" is shown on the left side of Figure 14. The upper trace shows the distillate composition responding to a step set-point change. Controller interaction causes the set point response to be quite slow since both controllers are working at cross purposes.

Decouplers are feed-forward elements where the measured disturbance is the controller output signal of another loop on the process. Two decouplers are required to compensate for loop interaction, one for each controller.[7] Like a feed-forward element, each decoupler requires identification of a process and disturbance model. The right side of Figure 14 shows that with decouplers in place, this loop interaction is dramatically reduced.

Students explore different controller modes, loop tunings, model structures, and many other design issues. With two controllers and four models for complete decoupling, students also learn how important bookkeeping is to the control designer.

CONCLUSION

Presented here are some examples of the lessons and challenges that a training simulator can provide. Space prohibits presentation of other studies available in Control Station, including the control of integrating processes, the use of the Smith predictor controller that is a simplest form of a model predictive controller, and a host of process identification methods and procedures.

We stress that we do not believe a training simulator is better than or a replacement for real lab experiences. In fact, we believe that hands-on studies with actual equipment are fundamental to the learning process.

We are of the opinion, however, that a training simulator like Control Station can provide students with a broad range of meaningful experiences in a safe and efficient fashion. These experiences can be obtained risk free and at minimal cost, enabling students to feel comfortable exploring nonstandard solutions at their desk. We believe if a training simulator is properly designed, it can bridge the gap between textbook and laboratory, enabling significantly enhanced learning for process control theory and practice. If the readers would like to learn more, they are encouraged to contact Doug Cooper at

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or visit

<www.engr.uconn.edu/control>

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ASTutE: COMPUTER-AIDED TEACHING OF MATERIALS BALANCING

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The ASTutE (Automated Student Tutorial Environment) project[1,2] has created a computer-based tutorial resource that has been successfully used to teach material balancing. This ASTutE software works alongside tutors to help meet the challenge of teaching students with increasingly diverse backgrounds while student-to-staff ratios continue to rise at the same time. The project is managed and staffed by the faculty of the Engineering Teaching & Learning Support Centre[3] at Loughborough University,[4] which is one of the leading institutes in the United Kingdom that encourages implementation of new technologies in teaching. ASTutE is being developed in conjunction with the engineering and science faculties at Loughborough University, with initial trials in the chemical engineering, mathematical sciences, and mechanical engineering departments.

Students use ASTutE interactively to check their answers to problems or as a detailed help system, but access only as much help as they require. Chemical engineering problems are often complex and best solved by following a prescribed method; ASTutE uses a variety of interactive information displays and question types to break such problems down into stages, guiding students to the solution. This approach encourages students to develop a methodological approach to problem solving. There are usually many ways to solve chemical engineering problems, and ASTutE provides feedback tailored to the responses of an individual student following one of many possible routes through a tutorial problem, consistent with their understanding of the topic. ASTutE solves simple, recurring student misunderstandings and difficulties, freeing academic tutors to deal with the more complex issues arising from the problems. A key feature of ASTutE is the ease with which tutors can quickly write new, or modify existing, problems by editing a simple template.

This paper describes the use of ASTutE at Loughborough to teach first-year chemical engineering students material balancing. This computer-aided learning (CAL) approach proved highly satisfactory for both staff and students and has a great potential for enhancing student learning.

MOTIVATION AND AIMS FOR A TUTORIAL RESOURCE

Chemical engineering, unlike many subjects in United Kingdom (UK) universities, has not been subject to an increase in student numbers. There has been an increase in the administrative load, however, and there is intense pressure for the professors to pursue and publish research. These two factors have reduced the available time for teaching, and coupled with increasingly diverse student backgrounds has left those professors who use traditional teaching methods struggling to cope. In order to maintain quality, which is now subject to rigorous external assessment, professors have needed to develop new teaching strategies.

Tutorials have been particularly affected by these pressures—most UK chemical engineering departments can no

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longer offer small-group tutorials. Yet tutorial work has always been an essential component in the consolidation of students' understanding of lecture material, particularly in subjects that are new to them. Traditionally, sheets of problems were handed out and then small groups of students discussed and solved any difficulties with the problems, guided by an academic tutor. The material balances module, described in this paper, was once taught entirely by solving tutorial problems. But because of the increase in group sizes, "discussing and solving difficulties" on an individual basis has become more and more difficult; students are less motivated to attempt problems, and tutorials degenerate into problems classes where the tutor solves the problems with little student interaction. This is unsatisfactory for those students of lower ability and those with nontraditional backgrounds—those who might hold vocational qualifications, or have graduated from a conversion course from arts to engineering, or have returned to academe after a long period outside of full-time education. These students require even more individual help than was available in the past, at least in the critical early stages of chemical engineering education.

The first author thought that CAL might offer a way of enhancing his teaching and overcoming these difficulties. He collaborated with the ASTutE developers to produce the material balances tutorial resource, with the aim of making these tutorials more effective for all involved.

To achieve this aim, several criteria for the tutorial resource were identified:

- *It must be integrated into the curriculum.*
- *It should be incorporated into existing courses without major modification, retaining the use of existing problem sheets.*
- *Tutors should be able to quickly and easily write or modify problems without recourse to special software and with a minimal "learning curve."*
- *It should be available at all times for use both in and outside of time-tabled sessions.*
- *The student interface must mirror the pencil-and-paper approach as much as possible.*
- *Students must find it easy to use and be able to work at their own pace, taking the learning route they are best suited to.*
- *It should solve the majority of difficulties for the majority of students, freeing tutors to deal with more complex issues.*

It was found that these criteria could be best met by programming a bespoke system in the multimedia authoring language, Authorware.[5]

THE ASTutE TUTORIAL ASSISTANT

ASTutE encourages students to systematically tackle a problem in much the same way as they would on paper. This generally consists of reading the text and then working through the following steps: 1) create a diagram, 2) discover the problem data and add it to the diagram, 3) set a basis for calculations, 4) formulate equations to use, and 5) solve the equations. ASTutE replicates this method by displaying the problem text and then offering help, which is provided in five key stages corresponding to the steps above.

ASTutE was designed to be used in different ways according to student needs and abilities. Three scenarios are described below to show this flexibility.

Scenario 1 • The initial screen of an ASTutE problem, shown in Figure 1, presents students with an answer box in which to enter their answers. In this simplest scenario, ASTutE is used as an answer-checking system. Strong students who have already successfully completed a problem may log on simply to check their answer or perhaps to look through the model solution before moving on to the next problem. This is the quickest route through the problems written in ASTutE.

Scenario 2 • When students experience difficulty at a certain point in a problem or are uncertain about their chosen method, pressing the "I'm stuck" button on the initial screen brings up a help menu of key stages, shown in Figure 2. Students choose any key stage(s) of help they require—for example, choosing a basis. ASTutE provides specific help,

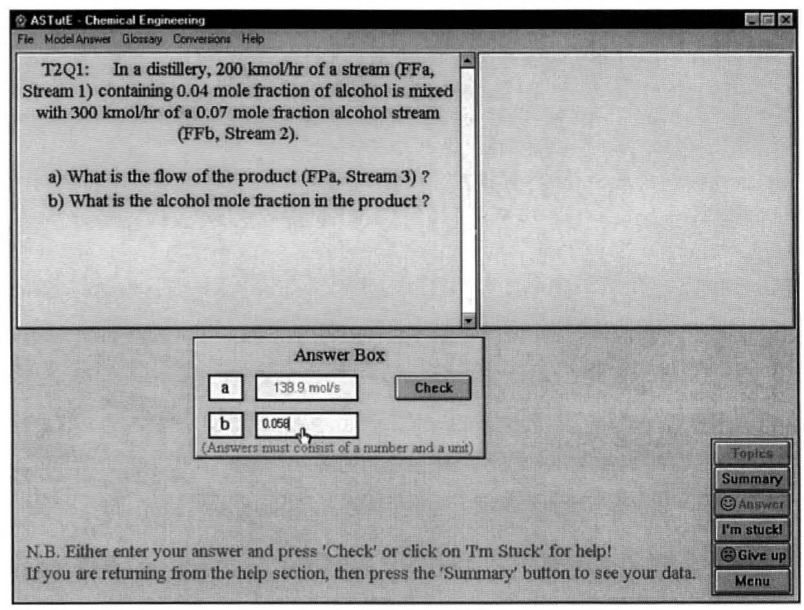

Figure 1. *Initial ASTutE screen displaying the answer box. The student can either input answers directly or click on "I'm stuck!" to access the detailed help system.*

Students use ASTutE interactively to check their answers to problems or as a detailed help system, but access only as much help as they require. Chemical engineering problems are often complex and best solved by following a prescribed method; ASTutE uses a variety of interactive information displays and question types to break such problems down into stages, guiding students to the solution.

solving the student's particular difficulty without solving the whole problem.

Scenario 3 • Weak students are led interactively, step by step, through a problem by accessing the help system from start to finish. They learn how to tackle a problem with logical methods, which will help them solve future problems.

ASTutE is a tutorial system and not an assessment system, and is therefore designed to be as flexible as possible. For example, the student is not required to create the diagram in order to be able to gain help on setting a basis for calculations, because these stages are independent. But the student will need to set the basis for calculations before solving the equations. Also, students are always able to input the final answer and can exit the help system at any point. This encourages the students to work on paper and try to solve the problems themselves, referring to ASTutE only as needed.

The feedback given to a student at any point is tailored to his or her individual responses. Students typically make one of a limited number of possible mistakes at any stage in a problem, and so the necessary feedback options can be identified relatively easily by a tutor. If an unpredicted but common difficulty emerges, the tutor modifies the existing problem template to incorporate it.

By catering to different student needs, strong students are not held back and the weaker ones are not too embarrassed to obtain the intensive help they need. It would be too ambitious and inefficient, however, to attempt to solve every conceivable difficulty for every student, so the tutor is always available to address the more complex or unusual misunderstandings.

QUESTION TYPES AND DIAGNOSIS

ASTutE supports an extensive range of basic question types, including multiple choice/response, text/number entry, hot spot, and drag-and-drop. Some of the complex questions types that have been created from these basic questions types are

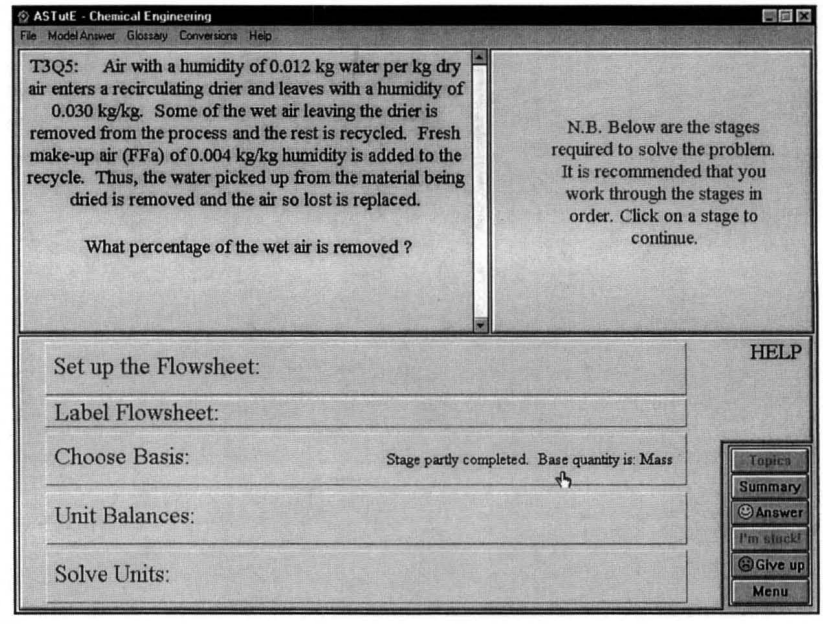

Figure 2. *The five key stages of a materials balance problem. A student has partially completed the "Choose Basis" stage, which then displays some summary information.*

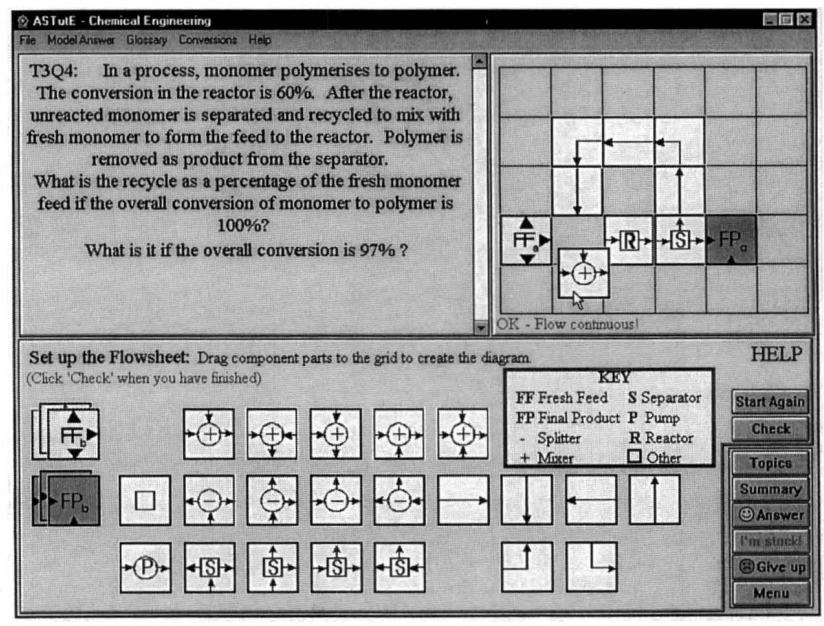

Figure 3. *The "Set up the Flowsheet" stage of a materials balance problem. A student is just about to complete one of the many possible correct flowsheet configurations.*

Number-Unit Entry • Students must provide suitable units with a numeric answer. The Dynamic Teaching Solutions project[6,7] developed the implementation. An example is shown in Figure 1.

Diagram Creation • Drag-and-drop allows flow sheets to be built up and labeled. This question type is illustrated in Figure 3.

Math Entry • Complex mathematical expressions can be entered in an easy and familiar way, as developed by Beilby.[8]

Multiple Response • Although this is a very straightforward question type, the diagnosis is complex. ASTutE allows the tutor to give specific feedback to any multiple response combination offered by the student.

WRITING PROBLEMS

ASTutE runs as an executable file, reading in problem data from text files. Tutors do not need to learn to use any special software. The text files are created or modified using any spreadsheet package. The tutor opens a problem template and follows the instructions in this file to write a problem.

ASTutE MATERIAL BALANCES TRIAL

We have used ASTutE in the Department of Chemical Engineering to provide additional tutorial assistance for material-balances teaching. Problem sheets were handed out in the normal way to a first-year class of 55 students who attended weekly 1.5-hour tutorials in a computer lab with 40 networked PCs running ASTutE and other CAL software. The first set of simple problems were presented in the first two weeks, using proprietary CAL software called Question Mark Designer.[9] Then, for the rest of the semester of 11 weeks, ASTutE was used. During the sessions, tutors circulated around the room and were available to help with the more intractable and/or uncommon problems that ASTutE could not solve. The tutors would also bring interesting issues that arose to the attention of the whole class.

Although we recommend *Elementary Principles of Chemical Processes*[10] as a text that students might like to consult as part of their learning process, ASTutE is self-contained and not tied to any particular book.

We believe that drawing and labeling diagrams is the key to understanding and then solving material balance problems, so these are the first two of the five help key stages shown in Figure 2 —"Set up the Flowsheet" and "Label Flowsheet."

Set up the Flowsheet (Figure 3) • Students create flowsheets by selecting individual elements from a library in the bottom half of the screen and placing them anywhere on the grid in the top right-hand corner. They receive instant feedback as components are placed—for example, if flow is discontinuous. Elements can be repositioned or removed at any stage. When students are satisfied with their flowsheet, they click the "Check" button and more feedback is given for flowsheets that have the wrong process units or are topologically incorrect. The tutor can provide specific feedback for specific errors.

When a student has constructed one of the (usually many) topologically equivalent correct flowsheets, ASTutE presents its standard version, which will be used from this point on. An example of a standard version is shown in Figure 4. Students must satisfy themselves that the standard diagram is equivalent to theirs. This encourages understanding of flowsheets and good drafting practice.

Label Flowsheet • Students first identify the chemical components in each stream of the standard flowsheet. Then they indicate where data specified in the problem text (which might refer to a stream, a unit, or the whole process) should be labeled on this flowsheet. On successful completion, a new annotated standard diagram is provided. In the example shown in Figure 4, the three pieces of data are: the input flow of "9" (gal/min), labeled above stream 1; the "21" (gal/min) flow through the pump; and the "3 equal demands" legend above the three splitters.

Choose Basis • First, students decide whether

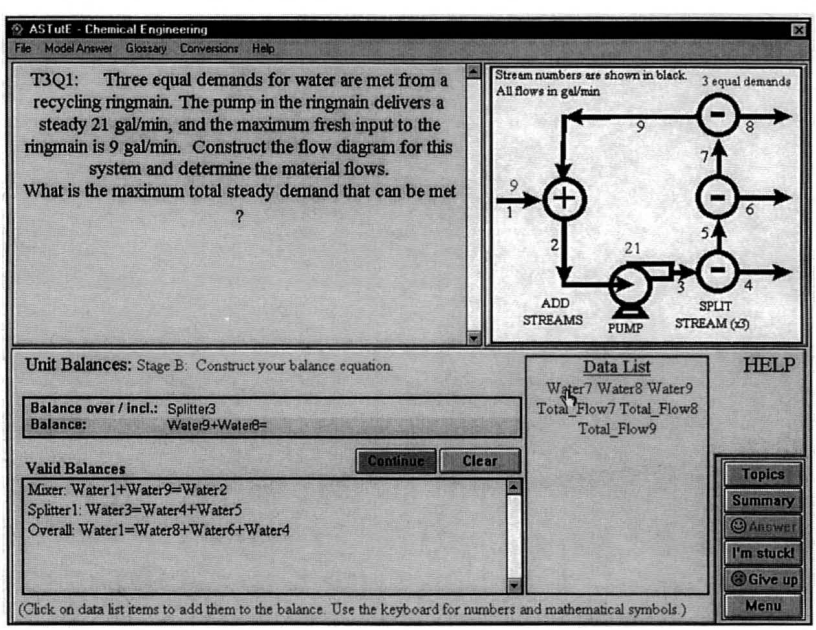

Figure 4. *The "Unit Balances" stage of a materials balance problem. Students can write as many equations as they feel necessary using the stream numbering system displayed on the annotated diagram. Each equation is checked for validity against the chosen basis.*

they will solve the problem using mass, moles, or volume flows. ASTutE gives appropriate feedback for each choice. Then students must select a stream, a component(s), and a flow value to use as the basis for their calculations. ASTutE comments on the desirability of their specified basis. All feedback has been written by the tutor in the problem text file.

Unit Balances • Students formulate balance equations, over flowsheet units or any part of the flowsheet, in terms of component or total flows. First, the site of the balance is specified—for example, over the entire flowsheet ("overall") or a unit ("mixer," "splitter," etc.). Then, as shown in Figure 4, the balance is constructed from the relevant in-flows and out-flows. In the equations, Water3, for example, represents the flow of water in stream 3. Each equation is checked for validity and against the chosen basis by ASTutE. Students may enter an unlimited number of valid equations and they are all added to the "Valid Balances" list.

Solve Units • Students see a grid with rows for streams and columns corresponding to components and with their selected basis value in the appropriate cell. They must fill in the component flows in each stream in order to complete the material balance. ASTutE checks that all flows entered in the grid correspond to the chosen basis. At any point, students may answer the problem or display a summary of help stages completed so far. When the student either solves the problem or "Gives up," a model answer consisting of text and diagrams written by the tutor is displayed.

TABLE 1
Student Performance on Materials Balancing Coursework

Statistic	*Year* 1997-98	1998-99
Number of students	57	53
Number that Achieved Full Marks	13	12
Number that Achieved Greater than 70%	48	47
Average Mark, %	87	84
Minimum Mark, %	32	56

TABLE 2
Student Scoring of ASTutE's Usability (Scale of 1 to 5)

Interaction with courseware (difficult to easy)	4
Navigating through ASTutE (difficult to easy)	3
Manipulating the interface (difficult to easy)	4
Presentation of diagrams and pictures (poor to good)	4
Presentation colors (uncomfortable to comfortable)	4
Clarity of information presented (vague to clear)	4

TABLE 3
Student Scores for Interest and Confidence in Subject Matter

Score	*1*	*2*	*3*	*4*	*5*
Interest	0%	0%	70%	25%	5%
Confidence	2%	5%	49%	42%	2%

EVALUATING ASTutE

Informal Observations

Student attendance at the CAL sessions was better than that at the conventional tutorials held in previous years, and attendance did not deteriorate through the semester. Most students said that they liked the sessions. A conventional tutorial that was offered each week as an alternative to the CAL sessions was usually attended by only a few, if any, students. The students were much keener to attempt the problems rather than waiting, as they had done previously, for the tutor to present solutions. We feel that this is the most important benefit of using CAL—the students attempt the problems. It is unclear if this is because they like using computers, or because CAL presentation is more interesting than problem sheets, or they dislike writing attempts at solutions that might be seen to be incorrect in class, or the help system is immediately accessible, or computer interaction is less threatening, or for some other reason.

An unexpected benefit of the CAL approach was that many of the students naturally formed into working groups. They helped each other learn, using the computer as a shared resource/tool.

The software met all the development criteria—in particular, the most important factor of handling frequent or simple questions and thus freeing tutors to give individual help and to answer difficult and peculiar questions. The attitude of the staff was therefore extremely positive.

We were surprised that the CAL software was rarely used outside of the timetabled sessions. This may be because the students have a lot to do already and have no time for extra work, or that access to computers was difficult, or that they obtained the full benefit in the timetabled sessions.

A common student complaint, expressed many times over the years of teaching material balancing, is "I cannot start difficult problems." Students still had this complaint. ASTutE development will further address this issue by helping students deconstruct the problem text, discover its meaning, and translate it into a diagram.

Assessment Feedback

We switched from conventional problem classes to problems presented in CAL sessions in one semester. We took the view that freshman students would not know there was an alternative approach, so a clean break with tradition would be possible. In order to check our impression that the students were learning as well as they had in previous years, we gave them a conventional paper-based test after four weeks of CAL-based material balancing teaching. The test consisted of two difficult questions to be completed in a short

time. Most students complained that they were not given enough time, but most of them got good marks, and some turned in excellent papers.

The students attempted and handed in written coursework in the eighth week. This was an old exam question that had been personalized for each student by changing the data in the question. Table 1 summarizes the results for the trial year (98/99) and compares them to those from the previous year when CAL was not used. Both the proportion of the class achieving full marks and the proportion achieving first-class performance were almost identical for the two years. The average mark was down slightly in 98/99, but the lowest mark was significantly up, whereas there were four students in 97/98 who scored less than the lowest 98/99 mark. This indicates that the CAL approach particularly helped weaker students. We were most encouraged by these results.

Student Session Questionnaire

A class of 43 students was surveyed by questionnaire during and after using ASTutE. The survey data showed that most of the students were confident in using computers, and 80% of the students had used CAL courseware before; ASTutE was the first CAL experience for the rest of the sample.

The students gave scores (lowest, 1, to highest, 5) to different usability aspects of ASTutE. Table 2 presents the distribution of the scores; all aspects of its utility were at least in the satisfactory range.

Students scored ASTutE's effect on developing their interest and confidence in the subject matter. Table 3 shows that ASTutE increased interest and confidence in the subject for 30% and 44% of the students, respectively, while 7% of the them found it reduced their confidence in the subject—these were students who had very little or no confidence in using the computer.

The students' opinion about how ASTutE would be most useful was as

a) Revision material for self-access in your own time and space (36%)

b) Additional tutorial resource, used with the tutor present (27%)

c) A lab session when you are first introduced to the subject (19%)

The percentages for multiple selection were: (b)(c), 8%; (a)(c), 6%; (a)(b), 2%; (a)(b)(c), 2%.

CONCLUSIONS

Both informal observation and questionnaire data indicate that the first group of students exposed to ASTutE were happy to use it as a tool in learning material balances. It was interesting to use and thus encouraged active engagement and a deeper approach to learning.

Staff found the CAL sessions more satisfying than the previous conventional problem classes because they did not have to "replay" their solutions to an unresponsive audience a number of times and could focus on the more interesting and demanding questions posed by the students. While setting up the CAL materials is extremely time-consuming, it only needs to be done once and requires minimal ongoing maintenance work. It is not yet possible to judge if this effort is cost-effective because at this stage it was not practical to split the time spent on software development from that on problem entry. Although CAL increases choice and diversity in the method of learning, it decreases flexibility in content. The possible questions will always be constrained by the capabilities of the software, whereas the combination of the English language, numbers, and freehand sketches are practically unconstrained for setting questions and describing solutions.

Although we have only limited data so far, the learning outcomes as measured by formal coursework, tests, and examinations, all indicate that the students learned at least as much using CAL as they did when taught by conventional methods. The CAL approach seems to be particularly helpful for weaker students.

Overall, ASTutE has proved to be a useful tool for teaching material balances—one that we will continue to use and enhance. Most importantly, the students attempted the problems presented in ASTutE, and when all is said and done, engineering is a subject best learned by doing.

ASTutE is still under development, but it could in principle be made available to other institutions. ASTutE runs under Windows 95/98 or NT. Implementation of the software in these environments should be simple. Extra tutor effort would be in proportion to the number and complexity of new problems. More information can be obtained by contacting the author at <D.W.Edwards@lboro.ac.uk>.

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SIMPLE MASS TRANSFER EXPERIMENT USING NANOFILTRATION MEMBRANES

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Membrane technology is increasingly recognized as an important separation process with a wide range of applications in biotechnology, food processing, water and wastewater treatment, and gas separations. But at the undergraduate level, laboratory experiments involving membrane technology have been lacking. This is probably due to the fact that the preparations involved in setting up an experiment using a membrane are quite difficult. For example, in reverse osmosis the applied pressure needed is very high, whereas for ultrafiltration, the sample preparation and analysis is quite laborious.

This paper will describe a simple experiment using a nanofiltration (NF) membrane for determination of mass transfer correlations at the feed side of the membrane cell. Conceptually, this experiment will introduce the students to the concept of concentration polarization, separation due to charge of ions, and overall performance of an NF membrane. Experimentally, the students will be able to determine the mass-transfer correlations, which will involve dimensionless numbers such as Reynolds, Sherwood, and Schmidt—the "classical" chemical engineering numbers.

THEORY

A nanofiltration membrane is a type of membrane that has properties in between ultrafiltration membranes and reverse osmosis membranes. It is usually identified as having a negative charge and pore size of approximately 1 nm. The charge and small pore size mean it can provide separation based on the Donnan effect for charged molecules and ions and sieving effect for neutral molecules. As such, it offers a wide range of separation capabilities in many areas of interest.[1]

One of the major problems with any membrane operation is the occurrence of concentration polarization at the membrane surface. The solutes that are rejected are held back in a layer next to the membrane surface. This solute buildup is called concentration polarization.

Observed rejection is defined as

$$R_{obs} = 1 - \frac{C_p}{C_b} \tag{1}$$

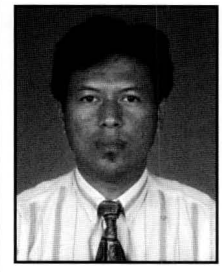
where C_p is the permeate concentration and C_b is the bulk solution concentration. It is an experimentally obtained measurement of the degree of rejection of the solute by the membrane. Due to concentration polarization, however, this definition of rejection is not accurate. The real concentration at the membrane interface is higher than the bulk concentration. Thus, the real rejection is defined as

$$R_{real} = 1 - \frac{C_p}{C_w} \tag{2}$$

The problem now is in determining the value of C_w, which is the concentration at the membrane wall. Figure 1 shows a schematic diagram of the interface between the bulk solution and the membrane surface for a three-component system. Concentration polarization close to the membrane surface is assumed to occur within a boundary film layer of thickness, δ. For a system containing charged ions, a mass balance for the film layer yields

$$j_i = -D_{i,\infty}\frac{dC_i}{dx} - \frac{z_i F}{RT}C_i D_{i,\infty}\frac{d\psi_f}{dx} + C_i J_v \tag{3}$$

where $D_{i,\infty}$ is the bulk diffusivity of ion i in the solution. The equation can be solved using the boundary conditions



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$$\text{at} \quad x = -\delta, \quad c = C_{i,b}$$
$$\text{at} \quad x = 0, \quad c = C_{i,w}$$

For a binary salt, the cation and anion will move together due to the requirement of electroneutrality. Equation (3) can be solved for both ions and the flux expressed as

$$j_+ = j_- = -D_{eff,\infty}\frac{dC_\pm}{dx} + C_\pm J_v \tag{4}$$

where $D_{eff,\infty}$ is the effective diffusivity of the salt defined as[2]

$$D_{eff,\infty} = \frac{D_{+,\infty}D_{-,\infty}(z_+ - z_-)}{z_+D_{+,\infty} - z_-D_{-,\infty}} \tag{5}$$

Using the boundary condition defined above, the wall concentration, C_w, can be correlated to other measurable parameters as

$$\frac{J_v}{k} = \ell n\frac{(C_w - C_p)}{(C_b - C_p)} = \ell n\frac{\left(\frac{1-R_{real}}{R_{real}}\right)}{\left(\frac{1-R_{obs}}{R_{obs}}\right)} \tag{6}$$

where k is the mass-transfer coefficient in the polarized boundary layer and is defined as

$$k = \frac{D_{eff,\infty}}{\delta} \tag{7}$$

This result is equally applicable to a system of neutral solutes. The mass-transfer coefficient is often characterized by a Sherwood number (N_{Sh}) correlation that is expressed as a function of Reynolds number (N_{Re}) and Schmidt number (N_{Sc}). For a laminar flow (N_{Re}<32000) in a stirred cell, the correlation is given as[3,4]

$$N_{Sh} = \phi(N_{Re})^n(N_{Sc})^{0.33} \tag{8}$$

$$N_{Sh} = \frac{kr}{D_{eff,\infty}} \qquad N_{Re} = \frac{\omega r^2}{\nu} \qquad N_{Sc} = \frac{\nu}{D_{eff,\infty}} \tag{9}$$

where r is the radius of the stirred cell, ω is the angular velocity of the stirrer in radians per second, ν is the kinematic viscosity defined as η/ρ, where η and ρ are the viscosity and the density of the fluid, respectively.

Another method of obtaining k is by extrapolating Eq. (6).[5] When written in linear form, Eq. (6) becomes

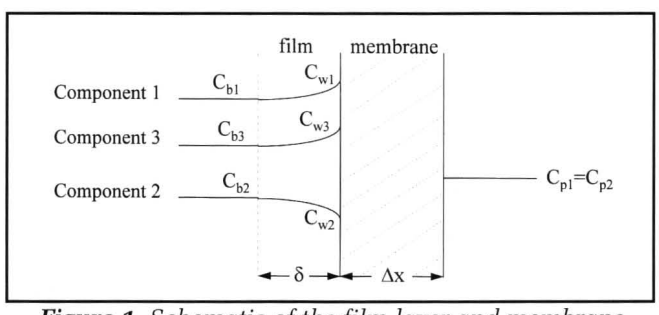

Figure 1. *Schematic of the film layer and membrane for three-component system.*

$$\ell n\left(\frac{1-R_{obs}}{R_{obs}}\right) = \ell n\left(\frac{1-R_{real}}{R_{real}}\right) + \frac{J_v}{k} \tag{10}$$

k was found to be a function of the stirring speed, and thus from Eq. (8), k can be written as a function of ω as

$$k = k'\,\omega^n \tag{11}$$

where

$$k' = \left[\phi\left(\frac{r^2}{\nu}\right)^n\left(\frac{\nu}{D_{eff,\infty}}\right)^{0.33}\frac{D_{eff,\infty}}{r}\right] \tag{12}$$

Thus, a plot of $\ell n(1 - R_{obs}/R_{obs})$ vs J_v/ω^n will give a slope of 1/k' and intercept of $\ell n(1 - R_{real} \backslash R_{real})$. The value of R_{real} obtained is the real rejection at infinite stirring speed. The most suitable values for n and ϕ have been determined by other workers using extensive sets of data and were found to be 0.567 and 0.23, respectively.[3,4] These values were used in this work.

MATERIALS AND METHODS

The experiment can be carried out either in a stirred cell or a cross-flow cell. In this work, the experiments were carried out using a stirred cell with an effective membrane area of 28.7 cm^2. The setup of the whole experiment is shown in Figure 2. A simpler setup involving only the stirred cell, the magnetic stirrer, the nitrogen flask, and a pressure gauge is also feasible. The pressure is varied from 100 to 500 kN m^{-2}. The membrane used was NF-PES5, obtained from Hoechst. The membrane has a pore radius of about 1.2 nm.[6] The concentration of NaCl used for the feed is 1 mM. The diffusivity values for $Na^+\left(D_\infty = 1.33\times10^{-9}\,m^2s^{-1}\right)$ and $Cl^-\left(D_\infty = 2.03\times10^{-9}\,m^2s^{-1}\right)$ were obtained from published work.[7]

The membrane should be soaked overnight in the pure water solution. For the experiments, the following procedure was used:

1. In each run, 180 ml of fresh solution was used as the feed solution. The stirring speed was set initially at 20 rpm and the solution was left for 2 to 3 minutes to equilibrate in the cell. The operating pressure was started at 100 kN m^{-2}.
2. After 20 grams (ml) of permeate was collected, the experiment was stopped. Then the conductivities of the fresh

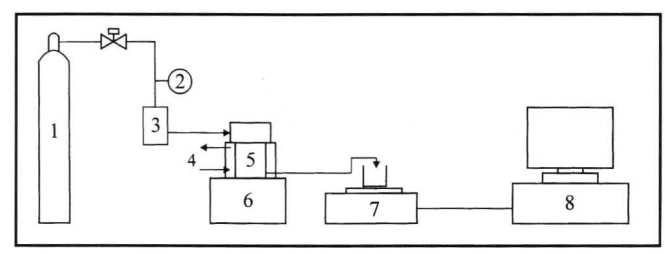

Figure 2. *Schematic diagram of dead-end filtration system. (1) nitrogen flask; (2) pressure transducer; (3) 250 mL reservoir; (4) water jacket; (5) filtration cell; (6) magnetic stirrer; (7) electronic balance; (8) personal computer*

solution, the retentate, and the permeate were recorded.

3. The conductivities of the feed solution, the retentate, and the permeate were converted into concentration using the conductivity calibration curve. The average bulk concentration in the feed was calculated as

$$C_b = \frac{C_{feed} + C_{retentate}}{2}$$

where C_{feed} and $C_{retentate}$ are the concentrations in the cell before and after the experiments, respectively. The observed rejection can be determined from Eq. (1).

4. The experiment was then repeated at the same operating pressure for the stirring speed of between 30, 50, 100, 200, 300, and 350 rpm.
5. The experiments were then repeated for operating pressures of 300 and 500 kN m^{-2}.
6. The weight of permeate collected against time was plotted and the data analyzed using linear regression. The slope of the plot represented the permeate flux in g/s or cm^3/s.

For a loose membrane such as NS-PES5, the flux is relatively large, and thus the experiments can be completed with three hours. But some membranes can be very "tight," and the fluxes are very low. Thus, careful consideration should be given in choosing which membrane to use.

RESULTS AND DISCUSSION

The experimental data were analyzed using the calculated k' obtained from the slope of Eq. (10). The data were then compared to the theoretical values obtained by using the calculated values of k' from Eq. (12).

Figure 3a shows the observed rejection of NaCl at three different pressures as a function of stirring speed for NF-PES5. It can be seen that R_{obs} changed considerably with stirring speed. The large changes were caused by the concentration polarization effect.

The data were then used to obtain k' using Eq. (10). Figure 3b shows the plot of $\ell n\left[(1-R_{obs})/R_{obs}\right]$ vs $J_v / \omega^{0.567}$. The lines are very linear, the calculated values of k' obtained by using Eqs. (10) and (12) are tabulated in Table 1 together with the values for $\exp(J_v / k' \omega^{0.657})$. This value is essentially the measure of the degree of concentration polarization. It can be seen that the error obtained when k' calculated by using Eqs. (10) and (12) is less than 5%.

The k' values were then used to calculate the experimental real rejection of NaCl. Figure 4 shows the real rejection as a function of the stirring speed. The filled points are those calculated using k' from Eq. (10), while the blank points are those calculated theoretically using Eq. (12). It can be seen that the effect of stirring speed has diminished, especially at larger stirring speeds. This means that the concentration polarization effect has been corrected. Agreement in the calculated real rejection using k' from Eqs. (10) and (12) are reasonably good, which means that the calculated k' from Eq. (12) can be used to estimate the mass transfer coefficient of the feed side.

An interesting observation is that the real rejection, R_{real}, was found to be dependent on the pressure drop. For nanofiltration membranes, this dependence is due to the fact that the rejection mechanism is not only determined by its intrinsic pore size, but also by the charge of the membrane (through the Donnan effect).[6,8] Furthermore, the transmembrane pressures used in this work produced fluxes in the range where the transport mechanisms of diffusion convection and electromigration are equally important, and thus the real rejection varied as a function of the applied pressure.[9] This behavior is different from the "standard" ultrafiltration or microfiltration membranes that show no dependence of

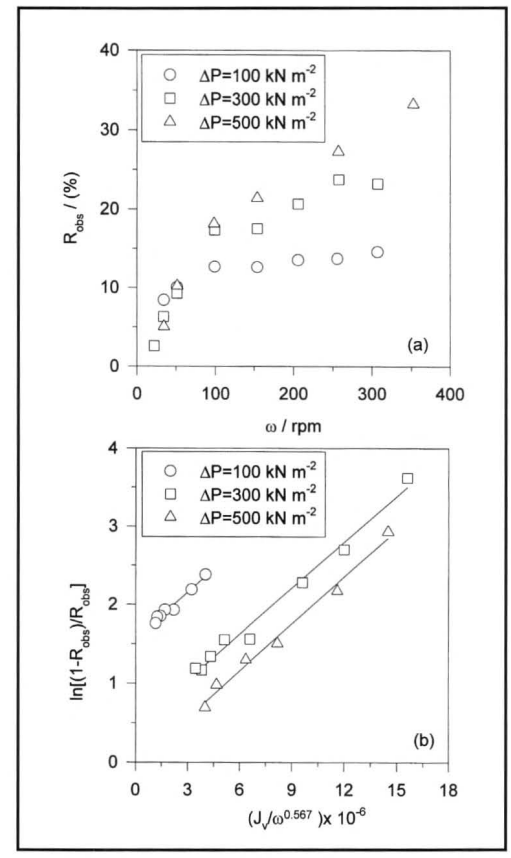

Figure 3. *Result for NF-PES5. a) Observed rejection as a function of stirring speed; b) linearization of the data to obtain k'.*

TABLE 1
Calculated Values for k' and the Exponential of the Peclet Number

Pressure	k'		$\exp(J_v / k' \omega^{0.567})$		
	Eq. (10)	Eq. (12)	Eq. (10)	Eq. (12)	% error
100 kN m^{-2}	5.02 x 10^{-6}	4.859 x 10^{-6}	1.26	1.27	0.8
300 kN m^{-2}	5.10 x 10^{-6}	4.859 x 10^{-6}	1.98	2.05	3.4
500 kN m^{-2}	5.02 x 10^{-6}	4.859 x 10^{-6}	2.58	2.66	3.0

R_{real} on transmembrane pressure at high fluxes where the transport of solutes is only through convection.

CONCLUSIONS

In conclusion, the experiments described here are very suitable for showing the concept of concentration polarization in membrane operations and how the "classical" mass transfer correlations are used to describe it. The equipment needed to run the experiments is quite easy to set up, and the experiment can be completed within the three-hour period normally reserved for the junior/senior laboratory.

The students should be able to make the following inferences/observations:

- *Concentration polarization is an important phenomenon in membrane filtration.*
- *A simple mass balance of the system allows one to deduce the mass transfer coefficient, which relates the solvent flux to the boundary concentrations.*
- *The mass transfer coefficient, k, can be calculated through an equation involving dimensionless numbers such as the Sherwood number, Reynolds number, and Schmidt number.*
- *The dimensionless equation can be confirmed through a simple experiment involving the measurement of rejection of a binary salt.*

For additional experiments, the correlations can be used to determine the diffusivity (by reversing the calculation method used here) value for another salt, such as KCl or LiCl (the student should not be told what salt they are using). The calculated diffusivity value can then be compared to the published data. This will be a good check on whether or not the students did the experiments correctly.

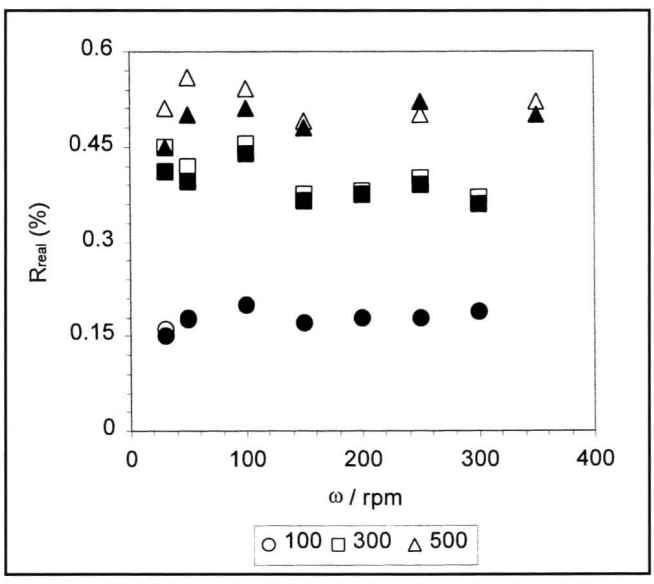

Figure 4. *Real rejection as a function of stirring speed. The darkened points show those calculated using k' from Eq. (10), while the clear points are those calculated using Eq. (12) The legend shows pressure drop in units of kN m^{-2}.*

NOTATION

C_b bulk concentration on the feed side of membrane (mol m^{-3})
C_i local concentration on the feed side of membrane (mol m^{-3})
C_p concentration in permeate (mol m^{-3})
C_w wall concentration on the feed side of membrane (mol m^{-3})
$D_{i,\infty}$ bulk diffusivity (m^{2}s^{-1})
$D_{eff,\infty}$ effective bulk diffusivity (m^{2}s^{-1})
F Faraday constant (C mol^{-1})
j_i ion flux (based on membrane area)(mol m^{-2}s^{-1})
J_v volume flux (based on membrane area)(m s^{-1})
k mass transfer constant (m s^{-1})
k' mass transfer constant defined by Eq. (8)
n constant defined in Eq. (8)
ΔP applied pressure drop (kN m^{-2})
r radius of stirrer (m)
R gas constant (J mol^{-1}K^{-1})
R_{real} real rejection
R_{obs} observed rejection
T absolute temperature (K)
x distance normal to membrane (m)
z_i valence of ion
δ thickness of film layer (m)
ϕ constant defined in Eq. (8)
η viscosity of solution (Pa s)
ν kinematic viscosity (m^{2}s^{-1})
ω stirring speed (rad s^{-1})
ψ_f potential in bulk solution (V)

subscripts

+ referring to cation
- referring to anion

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ISSUES IN DEVELOPING AND IMPLEMENTING AN ASSESSMENT PLAN

In ChE Departments

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Initially, the assessment requirements imposed by the new ABET Engineering Criteria 2000[1] appear daunting. Even the terminology is confusing. Compounding the challenge is the fact that engineering faculty typically lack experience in conducting outcomes assessment. Several authors have made analogies between the outcomes process of assessment and chemical process control loops.[2,3] Although these may be useful analogies for defining the purpose, they do not provide specific ideas on how to approach such a large and ill-defined problem as program assessment. No matter how hard we try, we cannot use Laplace transforms and transfer functions to make our problems go away. Instead, we must recognize that we will have to face these new challenges head-on.

The University of North Dakota was slated to be a pilot program for reaccreditation review under EC 2000 in the fall of 1997. Unfortunately, the massive flooding of the nearby Red River of the North in the spring of 1997 caused the accreditation visit to be postponed for one year. Although the flood was devastating to the city, the university, and faculty homes, it did save us from going up for accreditation prematurely. We were not ready! Like many programs that had been reviewed under the previous system, we did not realize how much lead time an organized and documentable assessment plan would require.

We had spent time rewriting mission statements and asking ourselves how we could determine if our students were really learning. Like most programs do, we saved everything: tests, final exams, lab reports, homework assignments, journal entries, etc. But we had no real plan as to what we should do with them. With the extra time afforded us by the flood, we began a series of discussions, planning sessions, and activities that helped us, finally, to address the pivotal issues. We were able to involve our constituencies by including students directly in the writing and planning and by meeting with our industrial advisory board. In the fall of 1998, the chemical engineering program at the University of North Dakota was visited under EC 2000. This site visit was the culmination of a two-year-long process (which really should have been longer) of preparing and implementing an assessment plan.

We wanted to write a paper that provided practical sugges-

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tions for reassessment that may not appear in a manual. The remainder of this paper is devoted to providing answers to questions that we struggled with and to providing advice for other departments.

QUESTIONS

How do we get started?

Schedule a relaxed meeting that does not occur during normal school hours or take place in your usual, more stressful surroundings. Use this meeting to discuss the steps and develop a timeline. Much of the accreditation and assessment preparation is sequential. Therefore, you will create your timeline for activities by noting your ultimate deadline for submitting your self-study to ABET (*e.g.*, June 1st prior to your accreditation visit) and working your way backward to the present. The major phases are

- *Selecting and writing about: vision, mission, goals, objectives, outcomes, indicators, practices, assessment methods, and assessment criteria*
- *Discussing and writing the self-study report*
- *Designing, pilot testing, and administering your assessment tools or collecting other data for assessment purposes*
- *Collecting materials for the various appendices to the self-study report*
- *Analyzing collected data*
- *Making changes to the educational experience based on your findings*
- *Assessing your improvements*

We cannot provide a timeline for you since all programs are different. Remember that you will need at least one complete cycle before your accreditation visit, so you must be done planning at least one year before the visit.

We were not ready! Like many programs that had been reviewed under the previous system, we did not realize how much lead time an organized and documentable assessment plan would require. . . we began a series of discussions, planning sessions, and activities that helped us, finally, to address the pivotal issues.

Should we get help?

Yes. Although assessment is worth it, it does add to already overburdened faculty workloads. Therefore, we hired an accreditation/assessment consultant who kept us on pace and helped translate the assessment-speak into ideas that we could understand. The consultant should not make decisions for you, but rather should serve as a facilitator in your efforts. One of the coauthors of this paper holds a PhD in higher education administration and had several years of assessment experience, so finding a consultant was easy for us. But almost all universities have a potential consultant in place. Some university personnel have been doing assessment for years. If you cannot afford (or do not prefer) an external consultant, try talking to individuals within your institutional research department or your college of education who may be able to recommend cost-effective assistance. Remember, a consultant should be just that—a consultant. He or she can help you greatly, but he or she cannot plan or do the assessment for you.

What do all these terms mean?

We recommend that early in the process you develop a set of common terms and definitions so that each of you will know what everyone else is talking about. Regrettably, there is no consensus in the assessment community. The important thing is that you all use the same terms and define them for the evaluators. We used the following definitions:

Vision statements outline your mission of the future.

Mission statements outline the purpose of your program.

Goals are the lofty aims. Things such as "We want our graduates to be effective communicators" are goals. You may wish to include university and college goals with your program goals.

Objectives are more specific. Perhaps things such as "When giving an oral presentation, our students will a) provide an introduction appropriate for a given audience, b) speak clearly, c) present facts in a logical manner d) support their arguments with facts and data, and e) clearly summarize key points.

Outcomes tell us what specific result(s) will occur, such as "Students will write effective documents."

Indicators are the specific items to which a "yes" or "no" answer to the outcomes questions can be applied, such as "Is the document formatted correctly?"

Practices are opportunities in your educational experience for student learning, such as a class or an activity.

Assessment Methods are the actual tools or other data-collection techniques you use to assess student learning, such as portfolios, alumni surveys, the Fundamentals of Engineering Exam, etc.

Assessment Criteria are the stated levels of performance for each assessment method that will be used to guide decisions and set priorities for improvement. You will want to develop those ideas that are unique to your program and highlight your strengths in addition to ideas required by outside bodies.

How can we make sure all of us are addressing criteria that we need to address?

Use various matrices to give you visual pictures of how your outcomes map to your curriculum and also to your assessment methods. Two sample matrices are shown in Tables 1 and 2. You should try to make sure there are at least three "hits" for every item in the rows and columns for each matrix. On the other hand, if there are too many "hits" in a row or column, you may be able to eliminate some in favor of addressing other desired areas.

How much data should we accumulate?

If you save every exam and homework assignment, you will be buried with so much data that you will be unable to figure out what is meaningful. By planning carefully in mapping instruments to your objectives, you can reduce the data collection considerably. Remember, assessment is not just "do it once and forget about it." Sampling is the key concept in data collection. In general, you should gather the least amount of data that will give you the most information. In other words, some assessment methods may require input from all sources, other may only require strategically selected samples. Whenever possible, use or modify existing data collection opportunities to reduce the burden of data collection. For example, your university might already be collecting information you need. You will want to do a project cost analysis (*i.e.,* in terms of materials and time) in conjunction with data collection and, in reality, this may impact how much data you can feasibly collect.

How do we keep track of things?

First, set up a data warehouse. You might want to include the following electronic folders for each program: self-study, syllabi, curriculum vita, tables, policies, references, (assess-

TABLE 1
List of Assessment Methods Mapped to Objectives

A = knowledge of math, science, and engineering
B = design and conduct experiments; analyze and interpret data
C = design a system, process, or component
D = multidisciplinary teams
E = identify, formulate, and solve engineering problems
F = ethics
G = communicate effectively
H = broad education to see societal impact
I = lifelong learning
J = knowledge of contemporary issues
K = use modern tools
L = working knowledge of chemistry
M = working knowledge of ChE principles
N = department-specific objective
O = department-specific objective

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Senior Design Reports															
Senior Design Orals															
Unit Ops Lab Reports															
Clinic Reports															
Clinic Presentations															
FE Exam															
Portfolios															
E-Portfolios															
Alumni Surveys															
Employer/Recruit Surveys															
Exit Interviews															
Peer Reviews															

TABLE 2
List of Practices Mapped to Educational Objectives

A = knowledge of math, science, and engineering
B = design and conduct experiments; analyze and interpret data
C = design a system, process, or component
D = multidisciplinary teams
E = identify, formulate, and solve engineering problems
F = ethics
G = communicate effectively
H = broad education to see societal impact
I = lifelong learning
J = knowledge of contemporary issues
K = use modern tools
L = working knowledge of chemistry
M = working knowledge of ChE principles
N = department-specific objective
O = department-specific objective

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
ChE Courses															
Senior Design															
Unit Ops Lab															
Internships															
Oral Presentations															
General Eds															
Chemistry															
AIChE, SWE, etc.															

ment) tools, data, and reports. Second, set up a data storage system for paper copies. Third, develop a timeline for the fall, spring, and summer semesters, with suggestions of what should occur early in the semester, in the middle, or at its end. Obviously, assessment activities should be distributed in such a way that allows for moderate activity throughout each semester instead of periods with too much or too little collection. Finally, make each faculty member responsible for at least one assessment activity. This way, all instruments will be used without any one faculty member being overburdened. Each coordinator should maintain a set of written responsibilities as a reference to facilitate administering tools.

How do we plan improvements?

There must be a formalized system in place. We recommend having a retreat during the summer each year, which we called the "assessment marathon." Over two days, we discussed all aspects of our program, including the data from each tool, in turn. We identified strengths as well as areas for improvement and made decisions affecting our curriculum and policies. These discussions were wonderfully productive, and we left with a better feel for the program as a whole.

How involved should we be with other departments?

We were not nearly as involved with the other departments in the college as we should have been. Although we shared information, an alumni survey was the only common instrument used. A significant aspect of the assessment process is discussions about improvement, and all departments can benefit from each other's experiences. Most university-level information is useful in assessing the general educational experiences that are likely to be common across the programs. It is important, however, to remember that accreditation occurs at the departmental level, so each department is ultimately responsible for itself.

Why won't anyone provide specific answers instead of just general advice?

Outcomes assessment is a highly personal activity. The whole point of moving away from bean counting and into outcomes was to enable programs to set their own goals, defend their importance, and prove that they are being achieved. Even a reviewer of an early draft of this paper asked "What should we collect—finals exams but not homework, materials from every student or every tenth student?" There are no single answers to these kinds of questions. A program that graduates 15 students a year will keep different information than one that graduates 100 or more. If final exams are one of five assessment instruments you are using to demonstrate that you have achieved an objective, you may not need homework as well. You own the process and must make your own decisions. Below is one education objective, as an example—but your department may have very different ideas.

Goal—*Develop students who communicate their ideas effectively in various formats to both technical and non-technical audiences.*

Objective • *The Chemical Engineering Program at Rowan University will produce graduates who demonstrate effective oral and written communication skills (ABET-G).*

Outcome A • *Students in the Chemical Engineering Program will write effective documents, including memos, e-mails, business letters, technical reports, operations manuals, and descriptions of systems, processes, or components.*

Indicators:

1. *Written at the appropriate level for the intended reader*
2. *Presents correct technical information*
3. *Contains few, if any, typographical or grammatical errors*
4. *Formatted correctly*
5. *Contains an introduction that interests and orients a reader*
6. *Contains a body that is relevant and covers important points*
7. *Contains a conclusion with summary and recommendations, when appropriate*

Practices:

1. *Chemical engineering courses*
2. *Unit operations lab*
3. *Internships*
4. *Senior plant design*

Assessment Instruments

1. *Senior plant design reports*
2. *Portfolios*
3. *Alumni surveys*
4. *Recruiter/employer surveys*
5. *Exit interviews*
6. *Peer reviews*

SUMMARY

The process of developing a workable assessment plan that is useful in preparing for accreditation under EC 2000 is long and filled with challenges. Departments must begin to analyze their program goals early and recognize the size of the task they face. Through progressive discussions and a systematic approach to planning, the task can be accomplished. Key points to remember include: identify your goals first, involve students and other constituents, minimize the data that you are required to collect and analyze, have multiple indicators for each objective (ideally involving multiple sources), and get started yesterday!

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A POLLUTION PREVENTION COURSE
That Helps Meet EC 2000 Objectives

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Today's engineer must be more aware of the environmental implications of technology than ever before. The last ten years have heralded a paradigm shift in the way engineers view environmental propriety; waste treatment is no longer the most acceptable means of dealing with process wastes. The Pollution Prevention Act of 1990 states that the option of first choice is to prevent formation of waste at the source.[1] Since it is unlikely that people will give up the products that improve the quality of their lives, it is imperative that engineers learn how to evaluate and minimize its environmental impact during the concept and design stage of a product or process.

Engineers are always faced with the challenge of implementing new technologies at minimum cost. With increased awareness of the impact of technology on the environment, engineers must also deal with the added constraint of optimizing processes for minimum environmental impact. But, today's engineering students get little, if any, training on analyzing a manufacturing process for its environmental impact. A required course on pollution prevention (P2) can remedy this shortcoming in the engineering curriculum.

In many respects, the P2 course serves as a second design course—one with the objective of minimizing the environmental impact of the process. This clearly complements the standard chemical engineering design course in which the objective is to minimize the cost of a process. Thus, the P2 course supplements the curriculum by providing an alternative context in which to view process design.

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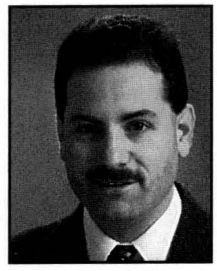

The ABET EC 2000 guidelines dictate several new challenges for engineering curricula, including the use of interdisciplinary teams, an awareness of the impact of technology on the world, and an appreciation for lifelong learning. We believe that all three of these items represent an essential element of environmental analysis. Thus, the pollution prevention requirement is an ideal environment in which to stress these elements of chemical engineering education.

HISTORICAL PERSPECTIVE

Recent chemical engineering literature has contained numerous references to the use of pollution prevention methods in industrial practice. Among the most frequent industrial proponents of pollution prevention have been Jim Dyer and Ken Mulholland of DuPont, the authors of a newly published book on pollution prevention.[2] Among their examples, they use the DuPont Chamber Works facility to illustrate that chemical engineers are taught the necessary tools to propose and test modifications in plant design that will lead to cleaner manufacturing processes. Old (and environmentally negligent) methods become entrenched within the system, however, making industrial leaders resistant to new technologies. Certainly, new engineers must be trained to seek the best environmental solution along with the usual economic design solution.[4]

In order to make engineers more aware of environmental problems, universities have recently begun instituting courses in waste treatment or pollution prevention, or discussing the issues of pollution prevention in their capstone design course. Some of these efforts are beginning to appear in archival publications. For example, Grant, *et al.*,[5] reported on a graduate course in pollution prevention that emphasizes waste audits and life-cycle assessment. More recently, El-Halwagi and Spriggs[6] described their use of a process simulator and mass integration as a basis for pollution prevention for senior/graduate chemical engineering students.

CURRENT PRACTICE

In order to gain more information about teaching pollution prevention, we conducted a survey of chemical engineering departments throughout the United States. Thirty-five programs provided information about their course offerings in pollution prevention. Including our course at the University of Toledo, we identified eleven programs that offer a stand-alone course in pollution prevention. One department teaches a course in industrial ecology as part of an environmental management program for engineers. Several additional departments (14) provide elective courses in some form of waste treatment and include pollution prevention as a component of the course. Six respondents indicated that they had no pollution prevention course, but taught the principles of pollution prevention in other courses, usually the senior design course. Only two respondents indicated that they offer no material in pollution prevention—these programs referred interested students to courses taught in other departments. To our knowledge, only our program required a pollution prevention course for chemical engineering students.

Additional information on pollution prevention course material is available through the University of Michigan National Pollution Prevention Center (as listed on the website at <http://www.umich.edu/~nppcpub/>, the Michigan State University Pollution Prevention Workshop at <http://www.p2workshop.org>, and the Canadian Centre for Pollution Prevention at <http://c2p2.sarnia.com>.

Without exception, each course described on the returned survey form is a one-term course (quarter or semester) and provides 3 credit hours toward the major. Class size averages between 15 and 20 students, and the typical course is offered once a year.

One goal of the survey was to identify the source material used in the development and delivery of a pollution prevention course. The majority of instructors listed Allen and Rosselot[7] as an assigned text for this course. Other books that were mentioned, either as a required text or as supplementary material, included those of Higgins,[8] El-Hawagi,[9] and Graedl and Allenby.[10] A recently published text[11] may also serve as a valuable resource. In nearly all cases, supplementary material obtained through NPPC, EPA, or other industrial and environmental organizations, was used to augment the textbooks.

Because most of the courses use the Allen and Rosselot text, it is not surprising that they follow a similar structure. The typical course begins with an introduction to pollution prevention concepts, moves on to a discussion of pollution in a broad sense (often including an introduction to life cycle analysis), and concludes with an extensive analysis of chemical processes and the development of process synthesis tools. As an indication of the typical content, the course outline used for our course in the fall of 1999 is given in Table 1.

Our survey also revealed that many chemical engineering departments offer elective courses in waste treatment or pollution control, and most of these contain a pollution prevention component. In addition, several programs provide pollution prevention education within the capstone design courses. For these programs, pollution prevention accounts for approximately two weeks of a fifteen-week semester.

P2 COURSE ORGANIZATION

We have recently implemented a required course, "Pollution Prevention," describing methods that can be used to minimize the impact of chemical processes on the environment. The course contains three components: an introduction to environmental pollutants, a discussion of life cycle analysis, and an environmental analysis of a chemical process. As a component of the course, we included a case study provided by a local chemical manufacturer.

After analyzing available resource materials, development of the course followed the outline in Table 1. It was designed as a stand-alone course on environmental issues in chemical engineering, focusing on the methods that can be used to minimize the environmental impact of ChE processes. The course can be loosely divided into three sections: 1) defining the problem, 2) analyzing processes and products through their life cycle, and 3) designing environmentally responsible chemical processes.

TABLE 1
Example of Course Schedule (Fall, 1999)

Week Beginning	*Topic*	*Reading*
Aug. 30	Pollution in context	Rossiter, Chapter 1
Sept. 6	Pollution control: legal context	Chapter 2
Sept. 13	Energy production from fossil fuel	
Sept. 20	Alternate energy sources	
Sept. 27	Life cycle analysis	Chapter 4
Oct. 4	Life cycle analysis—the mechanics	
Oct. 11	Life cycle analysis case study—food packaging	McDonalds/EDF case study[14]
Oct. 18	Pollution prevention in unit operations	Chapter 5
Oct 25	Environmental risk analysis and solvent selection	Allen, 2nd ed., Ch. 6[18]
Nov 1.	Risk modeling	
Nov. 8	Emissions from unit operation	Chapter 6, 1-3; Chapter 7
Nov. 15	Pollution prevent. in reaction eng.—green chemistry	Chapter 6.4
Nov. 22	Flowsheet analysis for pollution prevention	Chapter 8.1
Nov. 29	Rigorous methods: design for the environment	Chapter 8.2
Dec. 6	Environmental cost accounting	Chapter 9

Each of the class units is accompanied by a project that must be completed by a team of students. Project descriptions are purposely left vague so that the teams can proceed in as creative a manner as possible. Each project requires that students obtain background information, ensuring that they will gain some experience in using reference materials. Finally, a written report is required for each project, enhancing the students' writing skills.

What is Pollution?

As an initial class exercise, the students work together in small groups to define a pollutant. They begin with very different ideas about pollutants and generally present vague notions of things that are either bad for the environment, hazardous, or unsightly. Throughout the class, we hone the definition until we arrive at an acceptable compromise, *e.g.*: "An undesirable substance or disturbance that causes harm to the ecosystem or serves no beneficial purpose."

Given this definition of pollution, we next move on to a discussion of pollution prevention, focusing on the Pollution Prevention Act of 1990. Specific examples are normally presented at this point. During the current year, we are focusing our discussion on energy production from coal combustion. To illustrate the difference between pollution prevention and pollution control, we consider the differences between flue gas desulfurization (in which SO_2 is captured for disposal) and coal gasification (in which coal is converted to CO and H_2, and sulfur is recovered). This topic also provides an opportunity to discuss alternative energy, sustainability and the use of biomass, and low-energy density systems such as wind power. Our discussion of biomass utilization provides an introduction into life cycle analysis, which whets the student's appetite for later material.

It is important that students gain an appreciation for the range of laws and regulations that affect wastes evolving from a chemical process. This course is not intended to provide a definitive discussion of all the regulations, however; a cursory overview of only the most significant laws is provided, with more detailed information included about the Clean Air Act because of its relevance to energy production. This also provides an entry for discussing a range of environmental problems, from global warming (planetary, decades) to acid rain (regional, years) to urban smog (local, days).

Life Cycle Assessment (LCA)

When evaluating a process or product, it is important to consider its entire life cycle to adequately assess its impact on the environment. For example, the development of an electric car shifts the emissions from the tailpipe to the power plant. If one only considers the vehicle, then one neglects the emissions from the energy production needed to charge the batteries and the impact of energy storage (*e.g.*, lead acid batteries), thus incorrectly evaluating the real effect of this change on the environment.

The Allen and Rosselot textbook[7] introduces LCA in Chapter 4 and provides a few specific examples for illustrative purposes. Numerous life-cycle studies have also been completed within the past few years, and rigorous quantitative methods for LCA have been developed. The Graedl and Allenby texts[10,12] are an excellent resource on LCA. Additional examples are contained in a set of homework problems compiled by Allen, Bakshini, and Rosselot.[13] In addition, the EPA provides life cycle assessments of several products in the form of EPA reports, many of which can be accessed through its web site. A particularly appropriate study is one completed by McDonalds and the Environmental Defense Fund on the comparison of polystyrene clamshell and paper containers for hamburger delivery.[14]

At the heart of the LCA is completion of a material-and-energy-balance problem, information that is well known to chemical engineering students. They have less experience in defining the system boundaries or in allocating streams to individual products, but this can quickly be addressed through the material-and-energy-balance analogy. The students are accustomed to the necessary information being included in the problem statement, however, and are not aware of the level of difficulty encountered in obtaining the data necessary to complete an LCA or the problems associated with the quality of data. This is best illustrated using published studies wherein large volumes of data are compiled and evaluated (see the large list of information available through NPPC or the EPA Office of Pollution Prevention and Toxics).

Another component of the LCA that is new to the students is the assessment stage, where process effluents are compared to evaluate the environmental impact of a particular product. Although several techniques have been published in the literature, we have chosen to address this issue using the streamlined life cycle assessment (SLCA, described in detail by Graedl[15]). In this case, the raw material and energy uses and the process emissions are evaluated and ranked on a scale of 1 through 4. The total score of the product is then calculated, with the highest score representing the more environmentally friendly product. Using SLCA provides a means of converting the data obtained by the students into a quantitative measure of environmental friendliness.

In order to assess the student's ability to complete an LCA, we asked them to evaluate two different products that serve the same purpose. For example, students compared paper cups to styrofoam cups, or disposable diapers to cloth diapers, using the methodology described in class. Students were grouped into teams of two, with the idea that each of them could evaluate one product. They compiled the data using resources available at the library or through the internet, and then assigned a quantitative score to each of the components in the SLCA matrix. They then completed the analysis by identifying any important environmental issues that were not captured through this ranking system. The students com-

pleted the assignment by preparing a short technical report describing the results of their analysis.

Environmental Analysis of Chemical Processes

Because our course is designed for chemical engineering students, we put significant emphasis on the design of environmentally friendly chemical processes. Two components comprise this analysis: first, students must be able to evaluate the emissions from a particular unit operation or to design the unit operation to minimize its environmental impact; second, they must evaluate entire processes to determine where new technologies or new flow patterns could be implemented so that higher yields or selectivities can be achieved.

In evaluating specific unit operations, students must implement material they learned in the undergraduate curriculum to achieve their goal of minimal environmental impact. For example, we use equilibrium thermodynamics and mass transfer to estimate the VOC emissions from a vapor degreaser. Students complete the mass balance to determine the amount of solvent evaporated and then watch the emissions decrease when the solvent is changed to one with lower volatility. Similar calculations using fundamental methods describe how to estimate emissions from other vessels. Alternatively, the EPA and the American Petroleum Institute have compiled software tools to perform unit-specific emissions estimates, accessed through the EPA <www.epa.gov> or P2workshop <www.p2workshop.org> websites.

One can also consider optimizing an individual unit operation for maximum performance. Consider the design of a chemical reactor: suppose that two parallel pathways can occur, one producing the desired product and the other producing an undesired product. The reactor design textbook[16] teaches us that when the activation energy for the reaction leading to the desired product is greater than that of the other reaction, raising the temperature will improve the process selectivity. Thus, students must recall previously learned material or expand upon material that may have only been superficially discussed in previous classes.

A second component of this section is analysis of the overall operation of the plant to minimize the environmental impact of the process. Here, we use the concepts of the process-design course, along with the process simulator, but our objective is the minimization of waste streams. When we incorporate a technique for calculating the environmental impact of a process stream, we obtain a quantitative measure of the environmental impact of the proposed process.

We have used the Waste Reduction (WAR) algorithm developed by the EPA Risk Reduction Research Laboratory[17] as our basis for estimating potential environmental impact. Although several algorithms exist that could be used, WAR provides a consistent measure of estimating the environmental impact of each process stream. For us, WAR has two primary advantages: first, it is designed to work with the ChemCad simulator, the process simulator used in all of our undergraduate classes; second, WAR is being developed locally, so the developers are accessible to our students. We asked one of the researchers developing the algorithm to present the methodology to the class in a guest presentation. This researcher then served as a consultant to our class as they used the WAR algorithm to work on the project.

A process analysis project served as the capstone assignment for the class. Working in concert with a production facility in Toledo, we developed a process based on their commercial plant for the manufacture of pentaerythritol from formaldehyde and acetaldehyde. The use of a local industrial process had both advantages and disadvantages. On the plus side, the students were able to visit the plant and observe the process in operation, the process presentation was made by an engineer involved in the operation of the plant, and they were working on a real problem. But because of proprietary needs, the company was reluctant to share all of the information about their process with the students. In addition, the process contained elements that were not easily simulated using ChemCad, obscuring some of the pollution prevention issues within the simulation difficulties. Of course, any process can be used for this analysis as long as data can be found in the literature to support the simulation effort.

Despite the difficulties that we had in accessing proprietary information and implementing the pentaerythritol process on the simulator, the students were quite successful in evaluating pollution prevention opportunities for the process. For illustrative purposes, the results of two different groups' efforts are summarized here. In the original process, formic acid is used to neutralize the product stream leaving the reactor (the reaction must be carried out in basic media to facilitate the reaction). One group proposed using sulfuric acid, which converts by-product sodium formate into formic acid and sodium sulfate; the formic acid is converted to methyl formate (a salable product) while the latter is recovered as sodium sulfate (also a salable product). Analysis of the economics of the modified process showed a potential 17% cost savings relative to the cost of the original process. Use of the WAR algorithm, which reports potential environmental impact in terms of impact units of non-product per kilogram of product, showed a reduction in environmental impact of nearly 75%. Other groups focused more extensively on the inclusion of recycle streams. Nearly complete recycle could be achieved, decreasing the potential environmental impact by almost 99%. But, completing the recovery and recycle operations required installation of two distillation towers, a heat exchanger, and several pumps. Thus, the economics of this operation were not entirely favorable.

POLLUTION PREVENTION AND THE ABET EC 2000 CRITERIA

The ABET EC 2000 guidelines dictate several new chal-

lenges for engineering curricula that can be met, in part, through the P2 class. In particular, this class impacts five of the nine expected program outcomes, including

f. an understanding of professional and ethical responsibility
g. an ability to communicate effectively
h. the broad education necessary to understand the impact of engineering solution in a global and societal context
i. a recognition of the need for, and an ability to engage in, life-long learning
j. a knowledge of contemporary issues

In addition, the AIChE Program Criteria specified that students must achieve a "working knowledge, including safety and environmental aspects" of specific elements of chemical engineering. The pollution prevention requirement represents an ideal environment in which to stress these elements of chemical engineering education.

◑ **Outcome f:** Environmental considerations are an important component of a chemical engineer's professional responsibility. The pollution prevention course provides an excellent opportunity for addressing the ABET criterion on developing an understanding of those responsibilities. It places a major emphasis on environmental awareness, and in particular it focuses the students' attention on their role in minimizing the environmental impact of chemical processes. Course assignments require evaluation of the environmental impact of a chemical process and the engineer's responsibility in reducing that impact. We discuss alternative ways of meeting the environmental challenge, and even raise the issue of meeting the emissions standard by diluting the stream. Evidence that students understand their professional and ethical responsibilities is demonstrated through their evaluation of these issues within their project presentations.

◑ **Outcome g:** It is difficult to develop standard assessment tools (*i.e.,* exams) for complex environmental problems; thus, we assess the student's understanding through a series of written projects. These assignments require analysis of a problem and a discussion of potential solutions. A written report is normally the result of the student team's analysis. The reports are graded on both the technical content and the written communication. Because engineers must learn to communicate environmental issues in non-technical terms, this element is stressed with the report. Students demonstrate enhanced written communication skills by the improvement of their written reports over the course of the term.

◑ **Outcome h:** The framework of the P2 course includes a discussion of pollution, but pollution includes more than just evaluating the emissions from a chemical process. We also discuss the global impact of emissions in the context of global warming, ozone depletion, acid rain, etc. Perhaps the area in which this recognition is most clearly addressed is through life cycle analysis, which provides the class with a quantitative means of assessing the impact of a product or process on the environment. Within this evaluation, students must assign an importance to each environmental impact from a global standpoint. Their ability to describe CO_2 emissions in terms of its impact on global warming, and the different emissions levels achieved in process alternatives, demonstrates their understanding of the global impact of their decisions.

◑ **Outcome i:** Because environmental problems are constantly changing, assignments in this class generally require that students seek out data through which an evaluation can be made. We encourage students to look outside of the classroom to access data needed to solve the problem. Moreover, the assignments are framed in a general context. For example, consider this problem statement for an assignment on energy and the environment:

> *There is a wealth of information describing the electric utility industry, including detailed descriptions of numerous coal-fired power plants. You should identify a particular power plant and calculate (as best as possible) the overall efficiency of the plant. This estimate can be based on the amount of coal consumed in the plant and the amount of electricity generated. Also, estimate the emissions of CO_2, SO_2, PM, and NO_x in the plant, per unit of energy. Compare these values against industry standards (averages) to determine the plant efficiency.*

The students have been given guidance on where to find the required information, but the data are not provided. Moreover, the specific information required to solve this problem is not stated, although several different sources of data were identified. By requiring students to confront open-ended technological issues for which information must be sought outside the usual classroom/textbook sources, they experience the challenge and excitement of tackling problems as a professional does. Completion of the assignment demonstrates their ability to gain information and learn on their own.

◑ **Outcome j:** One of the primary technical issues in society today is the impact of technology on the global environment. Recent discussions in the popular press on global warming, loss of biodiversity, farmland, and habitat, on acid rain and ozone depletion, among other things, point to the importance of the environmental challenge we are currently facing. This is also the focus of the P2 course. Environmentally conscious design of all processes and products can minimize the environmental impact of the technical products that modern society demands. A completed LCA compares different products in a rational way and provides a tool for evaluating different alternatives and choosing the one that is most environmentally benign. Analysis of chemical processes, either individual unit operations or the entire process, teaches the students some simple techniques that can be used to reduce the environmental impact of these activities.

In direct response to this issue, a new component of the class has been introduced this year. Students are now asked to maintain an environmental journal, described in the current syllabus as:

> *Environmental Journal: Virtually every day there is an article in the popular or technical press regarding an environmental issue. Each student should collect articles throughout the semester and place them into a journal. After reading the article, the student should write a short (approximately 3-5 sentences) technical evaluation of the science and engineering basis behind the written article. Towards the end of the semester, the student should look for a series of articles from his/her journal on a common subject and prepare an extended evaluation (approximately 2-3 pages) describing the issue. Additional technical information may be required and should be cited, as necessary. The journal will be submitted on the last day of class.*

Clearly, the journal requires that the students remain aware of contemporary environmental issues within their own community and throughout the world.

COURSE EVALUATION AND MODIFICATIONS

The primary objective of the P2 course is to give students a different perspective on the design process and to demon-

strate the opportunities for using chemical engineering principles to minimize environmental impacts. For this reason, there is not a lot of new material presented within the course. Rather, it repackages many of the fundamentals learned in earlier courses and provides new insight into the use of these calculations. This was noted in student comments from an end-of-course survey completed in the fall of 1998. In a mid-course survey conducted in the fall of 1999, two questions explicitly requested information on this subject. Students agreed that the course shows that chemical engineering calculations can be applied in a new context and that pollution prevention is relevant to chemical engineering. Students also recognized that this course has limited technical content.

One of the primary issues raised by the students in the fall 1998 survey was the lack of exams and the reliance on projects. In general, students believed that the projects provided a good extension of the materials discussed in the class, but because grading a project tends to be more subjective than grading an exam, they felt that the grades did not reflect their learning. In addition, because the projects were group efforts, the students recognized that the project grade could reflect the abilities of a single member of the group and might not represent the capabilities of the others.

Based on the recommendations of these students, a series of quizzes was added for the following semester; the material for the quizzes came directly from lecture notes and provided an objective evaluation of each student's performance. In the fall 1999 survey, however, the students were neutral about the ability of the quizzes to provide a quantitative measure of classroom learning. Rather, they agreed that the projects were relevant to the lecture material. This conflicting information, obtained from different groups of students, points out the necessity of having multiple evaluation tools.

At the University of Toledo we are specifically interested in understanding how pollution prevention can be used to achieve ABET goals. In the spring of 1999, graduating seniors were asked to complete a survey matching the ABET goals with the course in which those skills were learned. Of 32 graduating seniors, 9 (28%) indicated that P2 was most helpful with regards to Criterion h, the broad education necessary to understand the impact of engineering solutions in a global and societal context. Additionally, 6 out of 32 (19%) listed Criterion j, a knowledge of contemporary issues. Similar information was requested from the mid-course survey conducted in the fall of 1999. Students agreed strongly that P2 teaches a knowledge of contemporary issues (Criterion j). The need for and ability to participate in life-long learning (Criterion i) and the ability to function on multidisciplinary teams (Criterion d) were also skills obtained within the P2 course.

SUMMARY

The pollution prevention course required of chemical engineering students at the University of Toledo provides a solid introduction to the role of the chemical engineer in controlling the future environmental impacts of chemical processes. The course describes the environment in a global context, forcing students to consider the far-ranging consequences of their engineering decisions. It reinforces many concepts taught throughout the chemical engineering curriculum and demonstrates new ways to apply the fundamental calculations that have already been learned. Because the concept of pollution prevention is still evolving and protection of the environment is a topical issue, this course provides an ideal environment in which to educate our students about the impact of engineering decisions on everyday life.

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A REAL-TIME APPROACH TO PROCESS CONTROL EDUCATION

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The classical approach to process control education of chemical engineering[1-4] has been to employ the frequency response methods of process control that were originally developed as pen-and-paper methods for the modeling of process systems. It has been evident for some time that the way process control is taught to chemical engineers needs to be updated.[5-11]

There is an academic requirement that the fundamentals of process control be taught in a more practical and concrete way than afforded by the traditional classical approaches. The increasingly overloaded degree syllabus provides additional impetus to reorganize subjects and reduce superfluous detail. Brisk and Newell[5] recommended training students "in how to utilize process control systems with just enough theory that they can understand what they are using and maintaining." They went on to lament that "unfortunately most of our institutions are teaching too much theory, very little on utilization and maintenance." Doss[6] comments in Edgar's round-table discussion on process control education in the year 2000[12] that "students tend not to retain the mathematical theory but to remember the experiences from control laboratory experiments and simulations." Ramaker, et al.,[11] point out that "an undergraduate in a chemical engineering curriculum [studying] process control should be taught using concepts that fit with the rest of chemical engineering education . . . maintaining the undergraduate curriculum as closely tied as possible to the time domain."

There is also an industrial imperative to teach material that is of use to the practicing engineer. Downs and Doss[7] noted that "what the [graduating engineer] needs is a base level understanding of differential equations, process dynamics, dynamic modeling of basic unit operations, basic control algorithms (such as PID), cascade structures, and feed forward structures. With these basic tools and an understanding of how to apply them, he can solve most of his control problems himself. What he does not need is the theory and mathematics that usually surround process control." The industrial imperative is further reinforced by comments such as the following that come from practicing chemical engineers working in process control or process operations:[8]

- *"I never made use of Bode plots or root locus when I was designing a control loop."*
- *"There are no transfer functions out there in the real plant."*
- *"The material I had been taught was of no use in commissioning a control loop.*

Control education clearly needs to do better.

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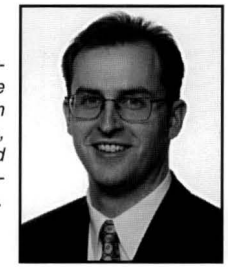

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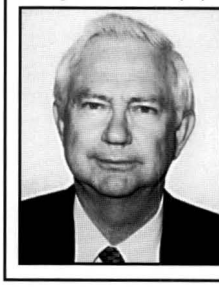

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CLASSICAL APPROACH

Classical control methods were developed between the 1940s and the 1960s in the mechanical and electromechanical engineering disciplines. Given the limitation of computer hardware and software at that time, it was impractical to solve large numbers of higher-order differential equations. Furthermore, since mechanical and electromechanical systems are typically linear and possess little dead time, they lend themselves to analytical and graphical techniques. Hence, there was the development and popularization of analytical and graphical techniques such as

- Transform methods (Laplace and Fourier Transforms)
- Graphical frequency domain methods (Bode, Nichols and Nyquist)
- Root locus analysis

Given the fit to their purpose, classical control techniques still prevail and remain relevant in these engineering disciplines today.

Although these methods make up almost half the content[4] of standard control texts,[1-3] they all share a number of deleterious characteristics. They all require a substantial amount of applied mathematics. In spite of the high level of mathematics required, in order to apply the analysis the system must first be made linear; the methods also have a transfer function basis, focus on individual units, and are generally good only for single loops and PID control. Limited multivariable and no plant-wide controls are possible.

Beyond the engineering deficiencies of classical techniques, there are also implications from a teaching and learning perspective. The abstraction of classical methods makes a difficult subject more difficult, and the methods lack physical meaning, obscuring the central problem of how to modify the system in order to achieve control.[8] These methods are also not suited to "what-if" studies, such as determining loop performance with parameter variation.

Today's ready availability of hardware and software has called into question the relevance of these classical methods for a primary course on process control. A number of previous workers have also identified this need for change. Many workers in the past decade have incorporated simulation software into the syllabus and deleted previous graphical procedures while retaining the classical methods. However, Brauner, et al.,[9] and then Stillman,[8] Bissell,[10] and Ramaker, et al.,[11] almost simultaneously proposed the more radical solution of complete replacement of classical methods with computer simulation, *i.e.,* not as an add-on, but as an integral part of the teaching and learning of process control. Ramaker, et al.,[11] possibly said it best when they said "this doesn't mean that the Laplace transform cannot be used as a tool to solve differential equations in the undergraduate course. Neither does it mean that frequency domain analysis and design are not useful in chemical engineering. It only means that we feel that frequency domain analysis and design should be taught at a graduate level, maintaining the undergraduate curriculum as closely tied as possible to the time domain."

In this paper we will outline and evaluate the actual implementation of such a complete real-time approach to process control.[13]

THE REAL-TIME APPROACH

Unlike mechanical and electromechanical systems, chemical processes are characterized by high degrees of nonlinearity, process interactions, and substantial dead time. Additionally, due to these non-idealities, chemical process control demands to be addressed with a multivariable and plant-wide view. As such, applying classical techniques to chemical process control is a bit like using a wrench to do a hammer's work. In an ideal world, the chemical engineer would have a "virtual plant" on which to experiment. It would capture most of the important non-idealities the real world imposes and would allow the engineer to readily test even the most outlandish of control structures with impunity.

Early attempts to realize this "ideal world" date back to the seventies and eighties[14] when dynamic simulators such as DYFLO, DYNSYS, or SPEEDUP first became available for the solution of nonlinear differential equations describing process dynamics. The hardware was slow at that time, however, and the software was impractical for students to learn and implement within a reasonable time frame. There was effectively no user interface in that the graphics were poor and the programs were run batch-wise.

In today's "simulation-rich" environment, however, the right combination of hardware and software is available for implementing a "real-time" approach to process control education.[14] The hardware and software, such as HYSYS, Aspen Dynamics, or MATLAB, is now fast and easy to use. Simple, complex, and/or user-defined process modules are available, and it is now easy to do "what-if" studies, multiloop, and plant-wide control simulations. The software user interface is now graphical and interactive, and the software can be painlessly run on a PC.

In short, the "virtual plant" has arrived.

This real-time approach also quite naturally lends itself to active, hands-on or resource-based learning.[15-16] In our course, we use a small number of lectures at the beginning to motivate students and to provide a fundamental understanding rather than simply transmitting information; we also use hands-on simulation tutorial sessions on case-study projects facilitated by the instructors, which we call workshops.[13] The syllabus covers the development of mathematical models to describe the transient real-time response characteristics of basic process elements, capacity, and dead time; fundamentals of single-input, single-output systems; use of a

dynamic process simulator; block-flow diagram of a feedback-control loop; process-control hardware; basic control modes; tuning feedback controllers; cascade control; feedforward control; common control loops; distillation-column control; design of multiple single-loop controllers; and plant-wide modeling and control.

We also note that while computer simulations provide generally favorable experiences, real experiments are still necessary and desirable.[17] Therefore, we employ in our course a cascade of tanks and a heat exchanger in a pilot plant laboratory that allows students to perform process identification exercises on real plants and to tune real controllers. So that the student understands the underlying "physics" of process control, modeling exercises that require the student to write the describing differential equations and solve them numerically using MATLAB are associated with these laboratory plant experiences.

A CASE STUDY

The real-time methodology will now be illustrated and compared with the classical approach by application to the feedback control of liquid level in a separator (see Figure 1). The unit of Figure 1 is usually represented by a system of transfer functions as shown in the block diagram for the liquid level loop of the separator, shown in Figure 2.

It is obvious that, from a learning perspective, the transfer function block diagram of Figure 2 bears no obvious relationship to the real plant in Figure 1, *i.e.,* the representation lacks physical meaning. Many assumptions and empirical determinations are necessary in order to relate the two. It bears repeating that the abstract nature of these sorts of classical methods makes the subject unnecessarily difficult,[8] obscuring the key issue of real process control, *i.e.,* how to modify the system of Figure 1 in order to achieve control.

In pursuit of the real-time approach, we need to find a better, more intuitive representation of the real plant. A better start is the word-block diagram of the separator liquid level loop shown in Figure 3. Although no underlying mathematics has been introduced, the word-block diagram illustrates the real process control situation of Figure 1 in a more physically meaningful way. The underlying mathematical representation of the process is the set of non-linear differential equations that can be written for each block and solved numerically or simulated by current process simulators such as HYSYS.

In the simulation approach, the student can now easily construct a real-time simulation given the input flow, tank volume, temperature, and pressure. Figure 4 is the plant process-flow diagram simulated in HYSYS, which shows a one-for-one match with the real plant.

The student can then easily indulge in "what-if" studies to find an optimal control structure and set of control param-

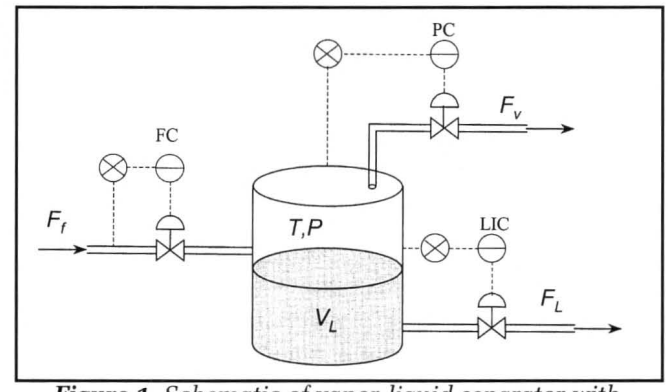

Figure 1. *Schematic of vapor-liquid separator with standard feedback controls.*

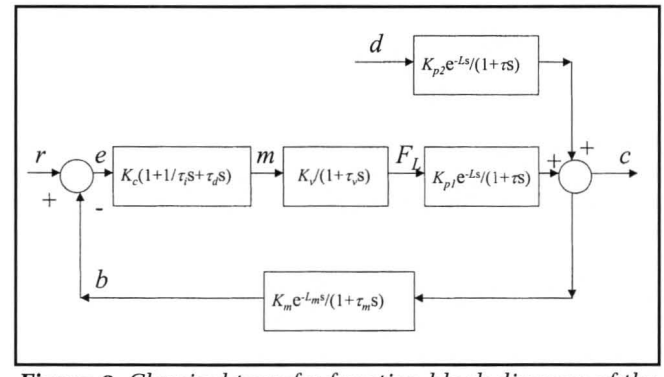

Figure 2. *Classical transfer function block diagram of the liquid level loop of the separator.*

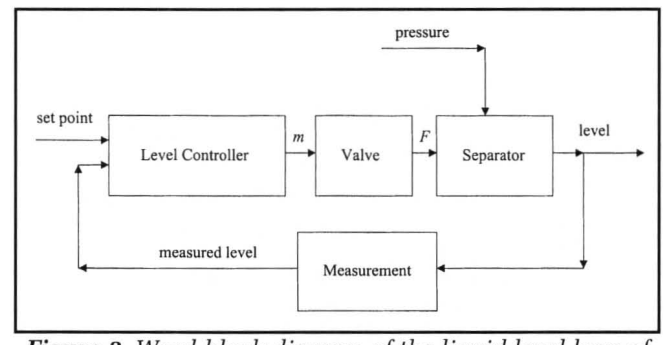

Figure 3. *Word-block diagram of the liquid level loop of the separator plant.*

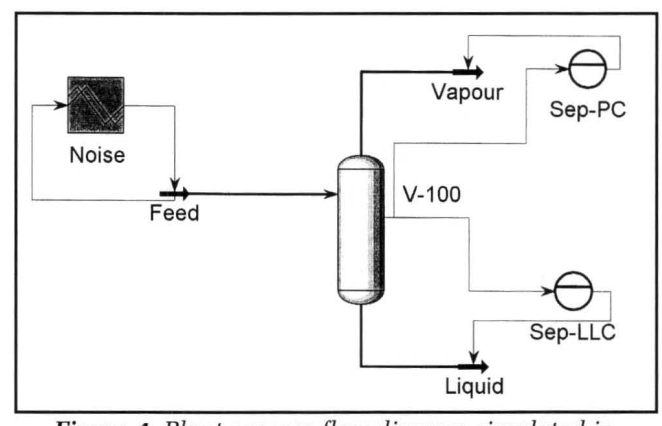

Figure 4. *Plant process-flow diagram simulated in HYSYS process.*

eters for the controllers—the fundamental air of process control. Figure 5 shows a screen shot of the simulated response of the separator to a step change in the set point of the liquid-level controller.

It bears mentioning again here that both the real-time and "what-if" studies described here are both difficult and extremely time consuming to perform when employing classical methods of process control instruction.

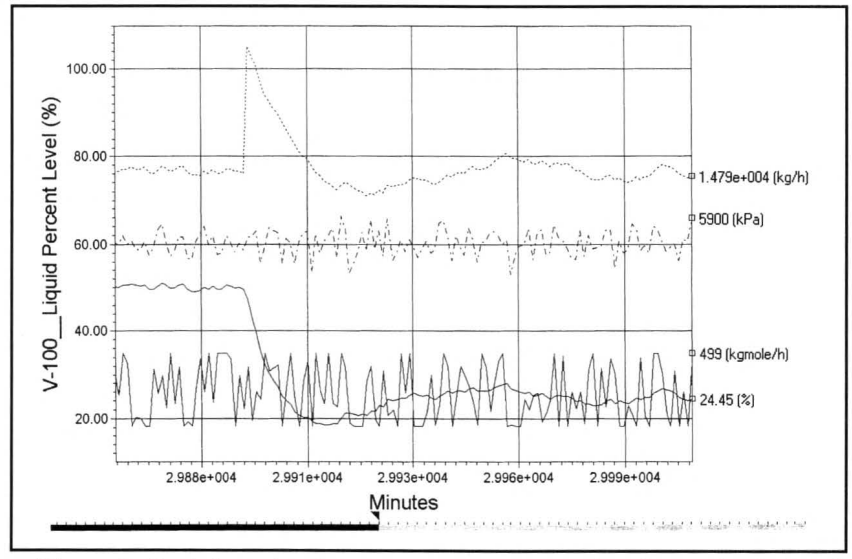

Figure 5. *Real-time simulator response to a set point change in the level controller.*

STUDENT EVALUATION

This real-time approach to process education was first developed in 1996 as a text and an associated set of workshops. This version was used at the University of Calgary during the 1997 academic year as a pilot course for nine students as their senior-year controls course. Their comments motivated a revised second version of the notes and workshops. This second version was used as the basis for the classes of 1998, 1999, and 2000, totaling forty-five, sixty, and eighty students, respectively. A further revision has just been published.[13]

As a means of generating feedback, the students were asked to complete a questionnaire. Overall, the overwhelming majority of students preferred the "hands-on real-time approach" to learning process control. More than 80% of the students said the approach was clear, concise, useful, and applicable. The major complaints, but only from a minority of students, were that they did not like "hands-on" self-directed learning, found the workshops too involved and time-consuming, and would have preferred a standard course consisting of standard lectures, assignments, quizzes, and a written final exam. Our anecdotal feedback from former students in industry is also overwhelmingly positive.

CONCLUSIONS

There is a need for change to conventional process control education—a change from a classical frequency domain methodology to instruction using concepts that fit with the rest of chemical engineering education, *i.e.,* a real-time approach.

A real-time simulation approach to undergraduate process control education in chemical engineering with the aid of realistic "hands-on" workshops involving real-time simulation of chemical processes was presented. The workshops are based on fundamental process models of industrial unit operations using educationally affordable and readily available commercial process simulation software. The real-time simulation approach to process control education was presented with the aid of a case study and compared with the traditional classical approach.

Student feedback from four years of implementation evaluated the new "hands-on" real-time simulation workshop approach as effective, useful, and applicable.

NOMENCLATURE

b	measured variable	c	controlled variable, proc. variable
LIC	level indicating controller	e	natural logarithm
e	controller input error signal, r-b	F	flow
K	controller gain	L	dead time
m	manipulated variable, control effort	P	pressure
PC	personal comp. or pressure controller	r	set point
s	Laplace transform variable	T	temperature
τ	time constant	V	volume
Subscripts			
c	controller	d	derivative or disturbance
f	flow	i	integral
L	liquid	m	measurement
v	valve	V	vapor

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ChE letters to the editor

To the Editor:

Professor Grossmann correctly points out errors that can occur when using citation statistics to compare graduate programs.[1] However, the differences between the results of the two studies that Professor Grossman considered (the National Research Council report[2] and Science Watch[3]) should not be used as a reason for discounting the value of citation statistics. The major difference in the results likely arises from a difference in what the two studies were designed to measure, rather than from errors. The NRC study attempted to measure quality of *departments or programs;* the Science Watch study compared *institutions.* Therefore, the NRC study reported citations arising from a single program or department within a university while Science Watch reported citations from the entire university. Furthermore, while the NRC study attempted to be inclusive and cover all journals, the Science Watch study covered a very narrow range of journals. For example, the Science Watch list included no electrochemical journals, no materials journals other than polymers (and only three of those), and only one biotechnology journal.

As a consequence, even without errors of the types noted by Professor Grossmann, the citation counts will vary greatly between the two studies. These differences could be in either direction. A university's chemical engineering activities would appear relatively weaker in the Science Watch study if it had major efforts in fields not included in the Science Watch journal list. Conversely, the chemical engineering activities would appear relatively stronger in Science Watch if the university had efforts in areas such a catalysis, surface chemistry, and combustion outside of the chemical engineering department. The Science Watch study is appropriate for comparing *universities* in the particular fields of applied chemistry and chemical engineering covered in the Science Watch database; it is not appropriate for comparing *chemical engineering departments* and should not be used for that purpose. The NRC study, which referred to programs rather than universities, has a more comprehensive database of publications and is appropriate for comparing chemical engineering programs.

Professor Grossmann is correct when he says we should use great care in interpreting countable indices such as citations and publications. However, it is possible to devise multiple, countable criteria that can give an alternative measure of graduate program quality.[4] Engineers, in particular, should not be reluctant to use countable indices rather than "reputational rankings." The "reputational rankings" give little more than historical perspective and cannot accurately portray a dynamic field such as modern chemical engineering.

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To The Editor:

At the risk of faning the flames of controversy concerning use of citation statistics in rankings of chemical engineering programs, I would like to add some comments engendered by the recent article by Ignacio Grossmann.[1] I do so from the point of view of a department that has admittedly fared reasonably well by current measures, as indicated below.

Professor Grossmann has pointed out some real and potential flaws in the citation statistics compiled by ISI and frequently used by one group or another to establish relative rankings of research programs in many fields, including chemical engineering. Assuming that errors arising from misspellings will tend to be randomly distributed, I would like to focus on some pitfalls that are far more serious.

A key issue is the definition of those journals that constitute the domain of chemical engineering that is sampled for both papers and citations. A glimpse of the journals in question reveals that they are what might be termed classic journals. However, the research carried out by chemical engineers today covers a much broader spectrum of activity than was true as little as 20 years ago. A prime example is the whole biotechnology area, ranging from biomedical to biochemical engineering, which is the major focus of an increasing number of chemical engineers. Accordingly, many of those researchers publish their work in widely read but "non-traditional" journals that do not fit into the "classical chemical engineering basket" used by ISI and hence do not contribute to the statistics generated. Incidentally, citations for chemical engineering from particular institution are based on publications in those journals regardless of the home discipline of the authors within that institution.

Of secondary importance, in my opinion, is the limited time window that ISI uses in gathering data, namely papers published and citations made during a particular time period. A more serious error is misinterpretation of the data that is based on small samples.

The various sections of Table 1 indicate some data recently obtained from ISI. I am, of course, pleased to cite these data in view of Northwestern's favorable position, particularly over the long range as shown in Part D. However, I would like to draw attention also to Part C, for the years 1994-1998. Those data show Georgetown University and the University of Hawaii, neither of which has a chemical engineering program, ranked among the first ten institutions on the basis of a very small number of published papers (one, in the case of Georgetown).

What is one to conclude from study of these data? I suggest that there are many reasons to be wary of attaching too much significance to citation statistics as they are commonly presented. They represent nothing more nor less than what they are, namely the number of citations per paper published in a specific group of journals. As such, they may prove to be of value for comparisons of departments with similar ranges of programs and activities, but they can hardly be afforded more significance without a great deal of further elaboration and reworking. In the last analysis, such reworking may not provide enough additional insight to warrant the efforts involved. Furthermore, the data show that significant fluctuations can occur in any year or short time interval, with some institutions suddenly appearing high in the list or drifting out of the first ten altogether from time to time.

Finally, Professor Grossmann has suggested that the impact of papers as measured by numbers of citations varies considerably from one journal to the next. While that is clearly true, it should not be taken as a condemnation or a devaluation of those journals that have large readerships. Clearly, such journals may in fact be widely read and quoted because of the quality and significance of the papers they publish, and faculty who are able to secure publication of their work in such journals may indeed have greater impact as a result.

(The assistance of Northwestern's Engineering and Science Librarian, Robert Michaelson, in gathering the data for Table 1 is acknowledged with thanks.)

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TABLE 1
Selected Citation Statistics, Chemical Engineering
(First 10 Institutions Ranked by Number of Citations per Paper)

Institution	Cites/Paper	Citations	Papers
Part A: Years 92-96 (5 years)			
Northwestern	5.97	734	123
Univ Virginia	5.67	397	70
Univ Pittsburgh	5.01	606	121
Univ Calif Berkeley	4.95	727	147
Univ Pennsylvania	4.78	344	72
Univ Delaware	4.63	768	166
Caltech	4.47	635	142
Lehigh Univ	4.39	501	114
Univ Wisconsin Madison	4.15	564	136
Ohio State Univ	3.67	286	78
Part B: Years 93-97 (5 years)			
Northwestern	5.96	697	117
Caltech	5.39	625	116
Univ Pittsburgh	5.12	681	133
Univ Calif Berkeley	4.55	692	152
Lehigh Univ	4.47	451	101
Univ Wisconsin Madison	4.26	558	131
Univ Delaware	4.18	703	168
SUNY Buffalo	3.94	512	130
Univ Minnesota	3.92	658	168
Univ Texas Austin	3.46	564	163
Part C: Years 94-98 (5 years)			
Georgetown	23	23	1
Caltech	8.7	531	61
Univ Hawaii	8.13	130	16
Northwestern	6.49	733	113
Univ Virginia	6.15	400	65
Univ Connecticut	5.77	202	35
Univ Colorado	5.66	487	86
Univ Penn	5.48	296	54
Univ So. Calif	5.42	195	36
Univ Pittsburgh	5.4	680	126
Part D: Years 81-97 (17 years)			
Univ Calif Berkeley	16.07	9241	575
Univ Wisconsin Madison	14.48	6663	460
MIT	14.15	7174	507
Northwestern	13.81	5484	397

COURSES IN FLUID MECHANICS AND CHEMICAL REACTION ENGINEERING IN EUROPE

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Professor H.E. Armstrong taught the first chemical engineering course in the world in 1885 at the Imperial College of London, and in 1888, Professor George E. Davis, Manchester University, published *Chemical Engineering*, describing a course divided into twelve lessons. At the same time, Professor L. Mills Norton established the first degree in chemical engineering at the Massachusetts Institute of Technology, where the first ChE department was founded in 1888. In Europe, Germany was the first country with ChE departments (1970) at the universities of Erlangen, Karlsruhe, and Dortmund.

In the first half of the 20th century, the ChE curriculum was focused on physical operations and industrial chemistry courses, but during the decade of 1955 to 1965, there were decisive changes; courses concerning transport phenomena appeared and were useful for unifying the physical bases of unit operations, followed by courses concerning fluid mechanics (FM) and chemical reaction engineering (CRE).

Understanding the phenomena and the principles that govern reactor behavior (*i.e.,* the study of CRE) is one aspect that currently distinguishes a ChE graduate from a physical or mechanical engineer. CRE is a general methodology for approaching any system where reactor engineering is required. The discipline uses different tools (mathematics, physics, etc.) to develop knowledge of the systems, especially the fluid behavior in the reactors. Consequently, CRE and FM are two disciplines very important to the ChE curriculum.

Books on these two disciplines are numerous. We would like to highlight some of them. As regards FM, a book by Cheremisoff[1] treats different aspects as the simple fluid flow, flow measurement, mixed-flow equipment, gas-liquid fluid flow, solid/gas, and solids. A book by Holland and Bragg[2] treats fluid behavior in a simple way, with some interesting examples. Books by Astarita[3] and Harris,[4] and in a singular way a book by Bird, *et al.,*[5] treat rheology and non-Newtonian fluid flow. Another book in this field is one by Coulson and Richardson[6] on fluid mechanics; this is one of the most-used texts in Europe.

With respect to CRE, the first major book appeared in the late 1940s as Volume 3 of the now-classical *Chemical Process Principles,* by Hougen and Watson.[7] This was followed by several books in the 1950s and 1960s, such as Smith's *Chemical Engineering Kinetics,*[8] Levenspiel's *Chemical Reaction Engineering,*[9] Astarita's *Mass Transfer with Chemical Reaction,*[10] and Danckwert's *Gas-Liquid Reaction.*[11] In the 1970s, a new series of books appeared with more emphasis on the analysis and mathematical modeling.[12-16] Out of all the CRE books, we want to highlight two by Levenspiel: *Chemical Reaction Engineering*[9] and *The Chemical Reactor Omnibook.*[17] The former presented the organization and systematization of CRE knowledge, and the recently published third edition[18] is an enrich-

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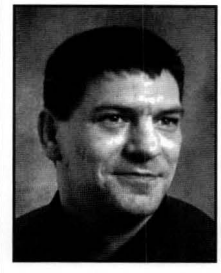

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The objective of this paper is to analyze the teaching of FM and CRE around Europe through a survey sent to over 100 European chemical engineering departments. The survey asked about time allocated to classes, books and tools used, and the number of students per class, among other things.

ment of the other editions with a structure similar to that of the *Omnibook*.

The objective of this paper is to analyze the teaching of FM and CRE around Europe through a survey sent to over 100 European chemical engineering departments. The survey asked about time allocated to classes, books and tools used, and the number of students per class, among other things. The results of this study will then be compared with the work reported by Dudukovic,[16] which analyzed CRE courses in U.S. and Canadian universities in 1982.

OBJECTIVES OF THE SURVEY

The European continent is changing rapidly. Nowadays, fifteen countries from the European Union (EU), together with Switzerland and Norway, form the European Economic Space, enabling citizens from each country to move freely between countries and to work in the other countries of the Space. Furthermore, since the fall of the Berlin wall in 1989, contact with the eastern block countries has increased to the point that Poland, Hungary, and the Czech Republic will most likely join the EU soon. This situation demands that European universities must now offer students a valid graduate degree that will be recognized in all the countries. As a consequence, university studies have undergone many changes. Chemical engineering studies are greatly affected by all these changes, and it has become necessary to determine what aspects neighboring countries consider most important in each of the ChE topics.

This paper will analyze how fluid mechanics and chemical engineering reaction topics are taught in the ChE undergraduate courses. Two surveys (one for FM and the other for CRE) were sent to a total of 107 universities throughout Europe (91 in the European Economic Space and 14 in the former eastern block). Responses were obtained from 68 and 70 ChE departments for the FM and CRE surveys, respectively, representing 63% and 65% of the departments con-

TABLE 1
Courses and Time Allocated to FM and CRE

	FM	CRE	CRE North America
1. *FM/CRE Courses Available for Undergraduates*			
One	31	22	69
Two	22	38	25
Three	33	21	5
Four	8	19	1
Five	6	0	0
2. *FM/CRE Courses Required for Undergraduates*			
One	49	48	91
Two	33	43	9
Three and more	18	9	0
Graduates			
None	52	57	27
One	41	31	58
Two and more	7	12	6
3. *Hours Allocated to FM/CRE Courses*			
a) Lectures/course			
Less than 20	12	11	-
21 to 40	47	40	-
41 to 60	26	40	-
61 to 80	12	3	-
Over 80	3	6	-
b) Problem solving/course			
Less than 10	15	17	-
11 to 20	41	33	-
21 to 40	38	33	-
41 to 50	3	11	-
Over 51	3	6	-
c) Laboratory/course			
Less than 10	36	46	-
11 to 20	36	14	-
21 to 40	25	20	-
41 to 50	3	6	-
Over 51	0	14	-
4. *Estimated Average Class Size*			
Basic FM/CRE	60	56	
Other FM/CRE	29	29	
5. *Experiments Available in Laboratory of FM/CRE*			
None	19	14	54
1 to 3	51	50	41
4 to 6	12	22	4
Over 6	18	14	1
6. *Industrial Input in FM/CRE Course*			
None	24	27	62
Some	67	70	34
A lot	9	3	4
7. *Describe the Industrial Input*			
Instructor had industrial experience	64	42	35
Case studies are treated	52	58	26
Instructor is from industry	6	6	9
Seminars by industry personnel	9	25	9
Field trips	30	22	7
Other	12	14	14

tacted. The responses were from the United Kingdom (29%), Spain (20%), Germany and Poland (9% each), France and Italy (6% each), and smaller numbers from the Czech Republic, Hungary, Ireland, Portugal, Romania, Slovenia, and Switzerland. The structure of the survey was similar to the one presented by Dudukovic for U.S. and Canadian universities in the early 1980s. Additionally, the results of the survey will be compared with the Dudukovic's results in the CRE field in order to point out the differences we observed between Europe and North America.

FM AND CRE COURSES: DEDICATED TIME AND ORGANIZATION

Table 1 shows the first seven questions of both surveys (FM and CRE), the corresponding results, and Dudukovic's data for North America. European universities offer an average of two courses of both FM and CRE. The number of universities offering one, two, or three courses is almost the same, whereas very few universities have additional courses for chemical engineering students. Contrarily, only 31% of the North American universities offer more than one course for CRE. Another important point is that almost 50% of the European universities require one course per topic for the undergraduate students, whereas the other 50% need at least one more; meanwhile, in North America there is a solid agreement (91%) for requiring only one course in the undergraduate program. As a consequence, it can be said that European universities offer one course more than required in the undergraduate studies program.

Question 4 asks about the average number of students per class. There is a homogeneous answer of 60 for the main course and 30 in other courses, which indicates good teaching quality.

The length of the different courses was analyzed by asking about the time allocated for regular-theoretical lectures, problem-solving seminars, and laboratory. Half (47%) of European FM courses require 20-40 hours, followed by 26.5% that require 41-60 hours. Problem-solving seminars are mainly grouped around 11-40 hours for both FM and CRE, whereas the time allocated to laboratory sessions shows wide disparity. For example, for CRE courses, 45% of the universities give more than 51 hours/course. The laboratory classes are directly related to Question 5, where the number of experiments available in laboratory classes is asked. Half of the European universities present 1 to 3 laboratory experiments per course, while fewer than 20% do not offer any. The North American survey showed that 54% of the universities did not give laboratory exercises, but obviously that situation cannot be extrapolated to the present time. The conclusion that can be drawn is that the number of universities that do not impart laboratory experiments has decreased to only 20%. On the other hand, nearly 20% of the universities currently offer more than 6 experiments, where only 1% offered such a number in the 1980s.

Another important aspect in the teaching of chemical engineering is the amount of industrial input in the classes. In North America in the 1980s, about 40% of the universities declared that they incorporated industrial input into the teaching, while in Europe today, over 70% of the universities indicate that they introduce industrial elements into the curriculum. It is important to point out, however, that in the North American survey only one answer per question was permitted, while in the European survey the universities were able to select multiple options; consequently, the comparison can only be done from a qualitative point of view.

For CRE instruction in North America, industrial input consisted of the professor's own industrial experience (35%) and the use of case studies (26%). A similar result was

TABLE 2
FM Topics, Objectives and Textbooks

1. Objectives of basic FM course as perceived by lecturers
(1=most important, 2= second most important, etc.)

Potential and internal flow	1.7
Biphasic gas-liquid flow	3.9
Piping, accessories, and pumps	1.8
Flow measurement	2.3
Filtration and sedimentation	3.4
Fixed and fluidized beds	3.9
Mixers, stirrers	4.1

2. Course dedicated to various key concepts

	Main	Other
Fluid systems	75	61
Solid fluid systems	25	39
TOTAL	100%	100%
Theoretical background	64	70
Descriptive background	36	30
TOTAL	100%	100%

3. Most frequently used textbooks for FM (multiple choice allowed)

Astarita, G[3]	9
Cheremisoff[1]	12
Coulson and Richardson (Fluid Mechanics)[6]	73
Davidson, et al.[20]	15
Holland and Bragg[2]	30
Kunii and Levenspiel[21]	21
Massey[22]	9
Darby[23]	9
White[24]	6
Levenspiel (Fluid Mechanics)	6

4. Did you replace the text in the last five years?

No	55
Only temporarily	16
Yes	29

5. Are current books satisfactory:

No	3
Somewhat	30
Yes	67

obtained in Europe. It is only remarkable that in Europe, 25% of the institutions reported that special seminars managed by industrial representatives were given. FM courses show different results; over 60% of the professors had previously worked in industry. Additionally, field trips to visit factories are also numerous (30%); it is possible that this percentage is bigger in Europe than in North America due to the fact that Europe is much smaller and distances are not a problem in planning visits.

TABLE 3
CRE Topics, Objectives and Textbooks
(previous data for North America included)

1. Objectives of basic CRE course as perceived by lecturers
(1=most important, 2= second most important, etc.)

	Europe	North America
Ideal reactors concept	1.7	1.6
Interpretation of kinetic data	3.2	2.4
Design of actual reactors	2.6	2.9
Reactor modeling and analysis	2.6	3.0
Kinetics and mechanisms	3.7	3.1
Transport kinetic interactions in heterogeneous systems	3.1	3.3

2. Course dedicated to various key concepts

	Main	Other	Main	Other
Homogeneous systems	63	28	77	35
Heterogeneous systems	37	72	23	65
TOTAL	100%		100%	
Ideal reactors	65	45	82	53
Non-ideal reactors	35	55	18	47
TOTAL	100%		100%	
Stirred pots	45	38	49	34
Tubular and packed bed reactors	47	44	33	48
Fluidized beds	8	18	18	18
TOTAL	100%		100%	

3. Most frequently used textbooks for CRE (multiple choice allowed)

Levenspiel[9]	75	58
Hill[26]	8	25
Smith[8]	30	14
Froment and Bischoff[14]	41	7
Fogler[15]	56	6
Carberry[12]	8	4
Levenspiel (Omnibook)[16]	39	-
Coulson and Richardson (Vol. 3)[28]	28	-
Westerterp, et al.[19]	22	-

4. Did you replace the text in the last five years?

No	56	44
Only temporarily	18	18
Yes	26	38

5. Are current books satisfactory:

No	6	6
Somewhat	30	37
Yes	64	57

TOPICS, OBJECTIVES, AND TEXTBOOKS FOR FM COURSES

In this section the results shown in Table 2 are analyzed. (In this case, no comparison with previous surveys or programs can be given.) Basically, there are two main groups in fluid mechanics: 1) the fluid dynamics, flow, and equipment (fluid systems), and 2) fluid dynamics when the fluid is in contact with solid particles (fluid-particle systems). The first question in Table 2 asks professors to rank seven parts of a fluid mechanics course in order of importance. The results show that "Potential and Internal Flow" and "Piping, Accessories, and Pumps" are the most important parts of the FM course, followed by "Flow Measurement." These three parts belong to the fluid-systems group and are considered by the instructors to be much more important than the fluid-particle system topics. Much lower in importance was the "Biphasic Gas Liquid Flow" and the areas belonging to fluid-particle systems.

These results are consistent with the answers obtained to the second question: 75% of course time is dedicated to fluid systems. For other more advanced courses in FM, fluid systems are still dominant, but at a lower level (61%). It is important to point out that in the survey some universities responded to both the main and the other courses, whereas some only responded to the main course, possibly due to the fact that they only require one course in the curricula. The analyzed results considered all the universities. Surprisingly, no differences were found and there is clear agreement that in the FM main course, fluid systems are considered more important and take more time than fluid-particle systems. It is also important to point out that for a main or other FM course, about 70% of the time is dedicated to theoretical aspects and 30% to a description of equipment and situations.

The textbooks favored by the instructors are analyzed in the third question. It is important to remark that the situation in Europe is very different from that in North America. The U.S.A. and Canada are English-speaking countries, while in Europe a huge number of languages live together in a much smaller land. Only books with at least an English edition were considered in this study since English is accepted as a second language in most European universities, although there is a clear tendency in Germany to use books of German authors written in German.

Most departments (73%) follow Coulson and Richardson's Chemical Engineering collection, which indicates a high level of agreement in teaching FM throughout Europe. Other general textbooks used are Holland and Bragg's *Fluid Flow for Chemical Engineers* (30%) and Cheremisoff's *Encyclopedia of Fluid Mechanics* (12%). Some other general textbooks are consulted by less than 10% of the departments, including those by Massey, Darby, White, and Levenspiel. It is noteworthy that several universities use the recently pub-

lished (1996) Darby book. Also, some books on specific topics are highly consulted, such as the books of Kunii and Levenspiel (22%), and Davidson, et al. (15%).

The answers to questions 4 and 5 in Table 2 reveal that a majority of instructors (95%) are satisfied, or at least somewhat satisfied, with the textbook used, and that 70% of them have not replaced the book in the last five years.

TOPICS, OBJECTIVES, AND TEXTBOOKS FOR CRE COURSES

In this section, the results for specific teaching objectives of CRE are presented, analyzed, and compared with the results of Dudukovic's survey of Canadian and U.S. Universities (see Table 3).

The first question asks the departments to rank the CRE courses as to their importance. The same topics were used as in the Dudukovic survey in order to make a direct comparison with the 1980s. In North America, the most important topic was the ideal reactors, followed by the interpretation of kinetic data and the design/modeling of reactors; reaction mechanism and transport kinetics had similar importance.

The present survey reveals that in Europe the ideal reactor concept is also the most important (1.8), followed now by the design, modeling, and analysis of actual reactors (2.6). Contrarily, all the aspects related to kinetics are secondary. In summary, the only difference from Dudukovic's results is that now the interpretation of kinetic data has a lower importance with respect to the design and modeling of reactors—perhaps due to the fact that some of these topics are covered in other courses.

The question concerning time allocated to different concepts shows that the principal CRE course is dedicated to homogeneous systems, while other courses are more specific for heterogeneous systems—very similar to the North American survey results. There is also agreement with the Dudukovic survey as concerns ideal/non-ideal reactors, *i.e.*, the basic course is dedicated to ideal aspects, and non-ideal concepts are dealt with in other courses.

For textbook analysis, the same criteria used in the FM section were used. In the 1980s, North American professors preferred Levenspiel (58%), Hill (25%), and Smith (14%), and the present survey showed that European professors also prefer the Levenspiel textbooks (*Chemical Reaction Engineering* with 75% and *Omnibook* with 40%). Other books that ranked poorly in 1980, however, are widely consulted in Europe today: Fogler (56%), Froment and Bischoff (42%), and Coulson and Richardson (29%). Again, it is important to note that over 95% of the professors are satisfied or somewhat satisfied with the textbook they are using.

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