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Washington University in St. Louis

Milorad P. Dudukovic*, John L. Kardos*, James M. McKelvey*, R.L. Motard*
Washington University in St. Louis • St. Louis, MO 63130-4899

The best-known symbol of St. Louis is the Gateway Arch, situated on the west bank of the Mississippi River in the city's downtown, and designated as the Jefferson Memorial National Monument. Another well-known St. Louis landmark, Washington University, was founded in 1853 and recently celebrated its sesquicentennial. The university, always an integral part of the St. Louis community, has grown from a nonsectarian "streetcar" school attended primarily by commuters to an international, research-based university.

The St. Louis Gateway Arch at dusk.

Washington University in St. Louis (WUSTL) has about 3,000 instructional faculty and 11,000 full-time students. The students are almost equally divided between its undergraduate divisions and graduate and professional schools. The university currently is tied for 11th place in the 2005 *U.S. News & World Report* rankings for undergraduate programs. Led by Chancellor Mark S. Wrighton, a chemistry professor, WUSTL has seven divisions: the College of Arts and Sciences, the Olin School of Business, the Sam Fox School of Design and Visual Arts, the School of Engineering and Applied Science, the School of Law, the School of Medicine, and the George Warren Brown School of Social Work.

** Rarely are four department chairmen still active within a relatively small department. The Department of Chemical Engineering at Washington University in St. Louis, however, is in such a fortunate situation.*

WUSTL received more than $533 million in research support in fiscal year 2005. A fund-raising campaign that ended on June 30, 2004, netted $1.55 billion.

The university's School of Engineering and Applied Science (SEAS) is a small, highly competitive but friendly place promoting high-quality education and research. The school's dean is Christopher I. Byrnes, a professor of applied mathematics and systems science who is well known for his contributions to nonlinear control theory. SEAS has six departments: biomedical engineering, chemical engineering, civil engineering, computer science and engineering, electrical and systems engineering, and mechani-

Brookings Hall, a Washington University in St. Louis landmark.

Lawrence E. Stout, WUSTL's first ChE chairman, pictured in 1940.

cal and aerospace engineering. It counts 1,200 undergraduates, 750 graduate students, and 88 tenured/tenure-track faculty. SEAS also has 35 endowed professors, six national academy members, five foreign national academy members, 17 national young investigators, and 59 fellows of professional societies. Fiscal year 2004 research expenditures were $42 million.

EARLY HISTORY

The name "Chemical Engineering" first appeared in Washington University catalogs in 1910 as a Bachelor of Science degree within the engineering school. Students were required to master concepts in general chemistry, analytical chemistry, organic chemistry, physical chemistry, stoichiometry, and industrial chemistry. They were also expected to familiarize themselves with technologies for producing clean water, food, milk, and milk products. Extensive laboratory work was required.

Between 1910 and 1930, few changes occurred in the curriculum. In this predepartmental era, chemical engineering courses were the responsibility of the Department of Chemistry in the College of Liberal Arts. It is noteworthy that **Lawrence E. Stout**, an associate professor of chemistry, was responsible for teaching the chemical engineering principles course as well as the chemical engineering laboratory and the engineering metallurgy course—all requirements for the ChE program at the time.

In 1940, the Department of Chemical Engineering was founded as an autonomous unit within the School of Engineering, and Dr. Stout was named its first chairman. The university's first master of science degree in chemical engineering was granted in 1941. The first doctorate was awarded in 1945. And the first woman with a B.S. in chemical engineering graduated in 1948.

POST-WAR ERA

The post-World War II era saw a sharp rise in ChE degrees at the university, cresting at 66 diplomas in 1949. In the 1950s, there was a modest increase in graduate work, and in 1959 the department's current home, Urbauer Hall, was built. By 1960, there were six full-time faculty members.

The addition of **James M. McKelvey** and **G.I. Esterson** to the ChE faculty brought about a notable change. The former focused on developing new approaches to quantifying polymer processing, and the latter embraced modern process-control techniques. *Polymer Processing*, the pioneering book written by Jim McKelvey and published in 1962, was the first of its kind and enhanced the department's reputation in teaching and research.

THE SIXTIES AND SEVENTIES

With Jim McKelvey (1962-1964) and **Eric Weger** (1964-1977) as department chairmen, the next two decades witnessed tremendous changes. During this era, the university gained international status. Moreover, the importance of graduate work and research grew, thanks in large part to increased federal funding. Biomedical engineering at WUSTL had an early start—and thrived—due to the prominence of the School of Medicine. Environmental concerns, new petrochemical and chemical processes, and the issues of energy and synthetic fuels all contributed to help make chemical engineering a popular major.

The undergraduate curriculum underwent a thorough transformation in these decades. Introduced in this period were mathematical analysis and modeling of chemical systems, transport phenomena as a basis for unit operations, quantitative treatment of chemical reaction engineering, process control, process synthesis, and design. New laboratory courses illustrated the key concepts of transport, unit operations, and chemical reaction engineering.

In summation, a curriculum that was firmly based on chemical engineering sciences emerged in the 1960s and—capitalizing on emerging advances in information technology—was augmented by process synthesis and model-based control in the 1970s. With modest changes, this successful curriculum remained in effect until 2000. Currently, a revised curriculum is being phased in.

Faculty additions and accomplishments

More remarkable than curriculum evolution in these two pivotal decades were changes that took place in research and graduate-level coursework. These changes were brought about by new faculty members and the synergism the department developed with the Corporate Engineering Division at Monsanto in St. Louis.

Professor John L. Kardos joined the ChE department in 1965, and in that year, the university and Monsanto were awarded a $1 million federal grant to develop the technology of composite materials. This government-sponsored university-industry program, the first of its kind, was part of a larger experiment by the federal government to learn how to couple universities and companies in joint research efforts.

The Washington University/Monsanto research effort was judged the most successful among seven such partnerships nationwide. From it emerged the engineering school's Materials Science and Engineering Program and an internationally recognized research group in composite materials. Today, this interdisciplinary program spans several engineering departments as well as other divisions of the university. On June 30 of this year, the professor so instrumental in its success, John Kardos, retired after 40 years of exemplary research and teaching at Washington University. He continues to provide advice and guidance as a professor emeritus.

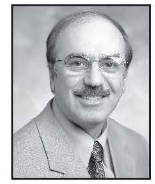
Others made their mark on the school's success as well. **Professor Buford Smith**, who joined the department in 1965, established a world-renowned thermodynamics laboratory for determination of vapor-liquid-equilibria in binary systems and for development of estimation methods for equilibria in multicomponent systems. In addition, Smith—with the help of **Dr. James Fair** and other Monsanto-affiliate faculty—developed a series of process-design case studies still used in classrooms worldwide. Upon Smith's retirement in the late '80s, his laboratory was purchased by DuPont.

Professor Robert Hochmuth (on the faculty from 1967 to 1978), pursued early biomedical research. An expert in the red blood cell membrane and its viscoelasticity, he developed unique experimental methods to test the effects of diseases such as sickle cell anemia on the membrane.

Professor Bob Sparks and **Professor Curt Thies** arrived at ChE in the early 1970s, and proceeded to put the department on the map

Chemical Engineering Faculty
at Washington University in St. Louis

Milorad P. Dudukovic, Department Chair
The Laura and William Jens Professor
Ph.D., Illinois Institute of Chicago, 1972
chemical reaction engineering, multiphase reactors, visualization of multiphase flows, environmental engineering, tracer methods



Muthanna Al-Dahhan
Associate Professor
D.Sc., Washington University, 1993
reaction engineering, multiphase reactors, bioprocessing engineering

Largus T. Angenent
Assistant Professor
Ph.D., Iowa State University, 1998
molecular tools for microbial ecology, anaerobic treatment of water and waste, bioreactor design and operation

Pratim Biswas
The Stifel and Quinette Jens Professor
Ph.D., California Inst. of Tech., 1985
aerosol science and engineering, air quality and pollution control, nanotechnology, environmentally benign processing

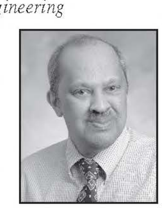
John T. Gleaves
Associate Professor
Ph.D., University of Illinois
industrial catalysis, microstructured materials

John L. Kardos
Professor Emeritus
Ph.D., Case Western Reserve Univ., 1965
structure-property relations in polymers and reinforced plastics, interface chemistry and physics of composites, processing science of composites

Bamin Khomami
The Frances F. Ahmann Professor
Ph.D., University of Illinois, 1987
transport properties of complex fluids, polymer physics, biomolecular physics

James M. McKelvey
Senior Professor
Ph.D., Washington University, 1952
thermodynamics, polymer processing, rheology, polymer technology

Rodolphe L. Motard
Senior Professor
D.Sc., Carnegie Mellon University, 1952
reaction engineering, multiphase reactors, bioprocessing engineering



P.A. Ramachandran
Professor
Ph.D., University of Bombay, 1971
chemical reaction engineering, applied mathematics, process modeling

Radakrishna Sureshkumar
Associate Professor
Ph.D., University of Delaware, 1996
complex fluid dynamics, interfacial nanostructures, multiscale modeling and simulations

Jay R. Turner
Associate Professor
D.Sc., Washington University, 1993
environmental engineering, air quality policy and technology, aerosol science and engineering

A bird's-eye view of Urbauer Hall, which is connected to other buildings in the WUSTL engineering campus.

in the area of controlled drug release and microencapsulation research. Sparks' research eventually culminated in the licensing of several patents and his retirement from SEAS in 1990 to found his own company. Thies became a professor emeritus in 2002 and continues to run his microencapsulation business from Nevada.

In 1974, **Professor Milorad P. (Mike) Dudukovic** arrived to start building the Chemical Reaction Engineering Laboratory (CREL), which now enjoys a world-class reputation. Funded by industry (18 companies from five continents) and government, CREL continues to be the most productive research unit in the department. Its focus is on the development of improved models and scale-up procedures for various multiphase reactors that are predominant in petroleum, chemical, and pharmaceutical applications.

Washington University was founded in 1853 and recently celebrated its sesquicentennial.

Dudukovic and his team have implemented novel noninvasive methods—gamma ray computer tomography and computer-assisted radioactive particle tracking—for monitoring phase distributions, flow, and mixing within multiphase contactors. The research team utilizes these techniques to validate computational fluid dynamics codes and to establish fundamentally based reactor models.

Dudukovic has also been long known as one of the most effective teachers at the university, and has been honored nationally and internationally for his pioneering research. Under his guidance, CREL has recently become a core partner with the University of Kansas, the University of Iowa, and Prairie View A&M University in the National Science Foundation Engineering Research Center for Environmentally Beneficial Catalysis (CEBC). CREL efforts for the center are focused on identifying the best reactor types for novel catalytic processes that lead to minimal impact on the environment.

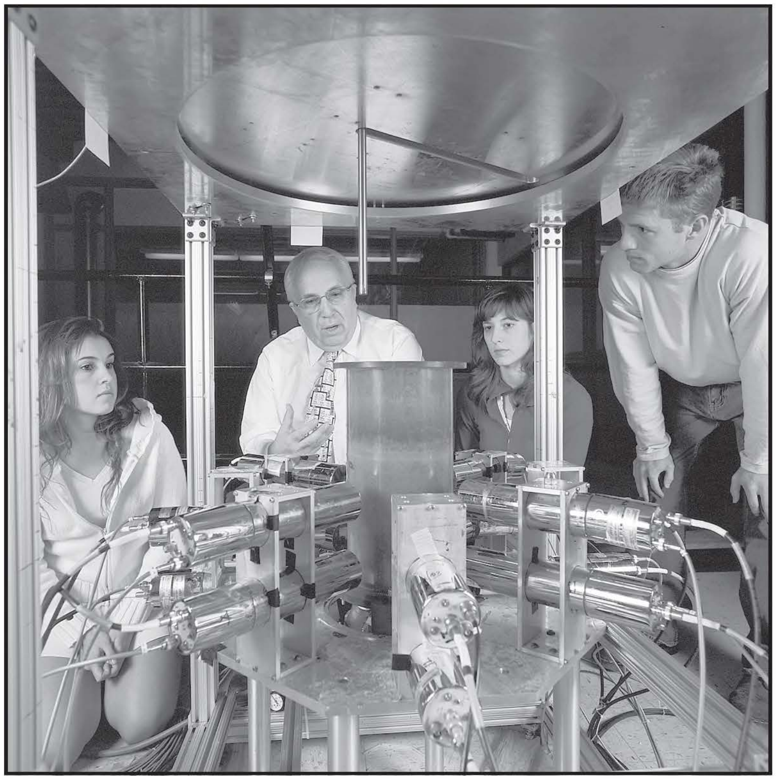
Professor Rodolphe L. (Rudy) Motard became the department's sixth chairman in 1978. Motard's research interests included flowsheeting, process synthesis, and data and information modeling—all of which have had a significant impact on industrial practice. He was one of the charter founders of the CACHE Corporation in 1968 and served as a consultant to the ASPEN development group at MIT. He also was instrumental in the formation of AIChE's Process Data Exchange Institute (pdXi). Motard became a senior professor in 1996 and continues to do research in process synthesis and database mining with the help of Yoshio Yamashita (D.Sc. '80).

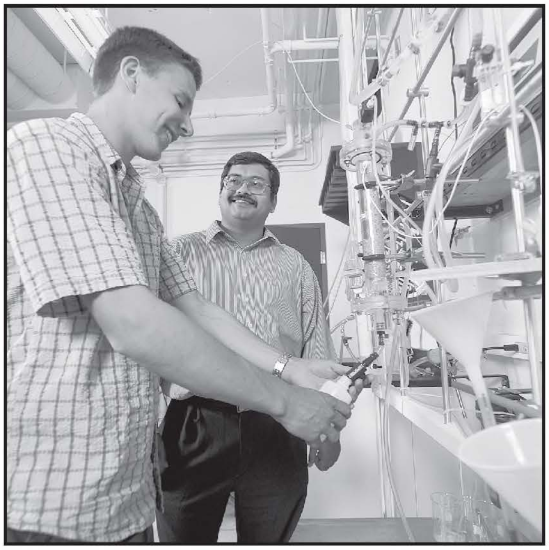
Professor Babu Joseph (1978-2002) worked with Motard to develop a cooperative effort in process synthesis design and control and sensor development based on wavelet transforms for early corrosion detection. Joseph also pioneered Web-based control experiments and the effective introduction of information technology in classroom teaching. He left the department in 2002 to become chairman of the ChE department at the University of South Florida in Tampa.

THE EIGHTIES TO THE PRESENT

The period of 1980 to the present has seen gradual change in the evolution of the undergraduate program—now firmly entrenched in chemical engineering science principles. Dur-

Right, ChE Chair and Professor Milorad P. (Mike) Dudukovic guides student researchers in the Chemical Reaction Engineering Laboratory. Below, Professor Pratim Biswas works with a student in the Air Quality Research Lab.





ing these years, the program embraced process synthesis and model-based control driven by information technology.

Professor P.A. Ramachandran joined the department in 1984. He has added a wealth of expertise in the area of applied mathematics and multiphase reaction engineering, and has strengthened CREL's chemical reaction engineering modeling activities. Ramachandran's research interests are in the modeling of heterogeneous reactions and the study of transport and reaction effects in design of chemical reactors.

His book, *Three-phase Catalytic Reactors*, published in 1983, is widely used even today by industrial practitioners as a first-reference source. Recent interests include pollution prevention strategies in chemical reactions, and design of green processes and reactors.

Non-Newtonian flows, polymer rheology, and processing were the main research interests of **Professor Bamin Khomami** when he joined the department in 1987. His current research focus is on the study of nonequilibrium transport and pattern formation in micro- or nano-structured media. Khomami's research involves studies of hydrodynamic instabilities and pattern formation in complex fluids, microdynamics of complex fluids, and synthesis of nano-structured particles and thin films via aerosol routes.

Professor John Gleaves came to the department in 1988 from Monsanto. He brought his Temporal Analysis of Products (TAP) system for probing of reaction mechanisms on real catalytic surfaces. Gleaves rapidly achieved worldwide acclaim for his technique, which has now been adopted at catalytic laboratories on four continents.

During the 1990s and beyond, the department added faculty to further support its research excellence in materials and reaction engineering, and to provide leadership in environmental engineering—an area targeted for growth by SEAS. John Kardos provided stable leadership from 1991 to 1998. Mike Dudukovic then became chairman and remains so at the present. During this period, more impressive faculty additions occurred.

Professor Jay Turner joined the department in 1993. Turner spearheaded the effort to reestablish environmental engineering as an interdisciplinary graduate-degree-granting program at SEAS. He established himself as a leading authority in the transport and monitoring of atmospheric aerosols, and has been in charge of a multiyear, multiuniversity project funded by the Environmental Protection Agency (EPA) and National Science Federation (NSF). He also has won multiple teaching awards at WUSTL.

In 1997, **Professor R. Sureshkumar** joined the department, bringing additional strengths in applied mathematics and physics of complex fluids. His research interests are nonlinear dynamics of complex fluids, interfacial nanostructures, and multiscale modeling and simulation. His work elucidating the physics of turbulent drag reduction by polymeric additives has been noted by theoreticians in the field and has had practical applications in saving pumping energy for farmers. Sureshkumar is the cofounder of the Chemical Engineering Learning Laboratory (CELL).

In 1998, Professor **Muthanna Al-Dahhan** was converted from part-time to full-time status to further CREL's chemical reaction engineering activities. Al-Dahhan has worked hard to expand CREL's industrial and governmental support. He also spearheaded CREL diversification into the biochemical area, where he has led projects in anaerobic digestor design and in photosynthetic reactions by algae.

Professor **Pratim Biswas** became director of the interdisciplinary Environmental Engineering Science Program in 2000. Biswas brought with him world-class expertise and recognition in aerosol generation, monitoring, transport, and applications. His Aerosol Research Laboratory team has established new applications of aerosol technology in generating catalysts for conversion of solar energy to hydrogen, for mercury abatement in power plants, and for water purification.

In 2002, Professor **Lars Angenent** joined the department, adding breadth to the Environmental Engineering Science Program and novel research initiatives. Angenent's traditional environmental engineering background led to his patent for an improved anaerobic digestor. He also has extensive experience in molecular-biological techniques. He is currently studying biological means for converting waste to electricity.

All members of our tenure-track faculty are very active in research, yet still teach one and often two courses a semester, senior professors included. In addition, we have a team of superb professionals—many of whom are ex-research fellows at Monsanto, Solutia, or Boeing— that contributes significantly to teaching and research as adjunct faculty. **Chuck Carpenter**, with over 30 years experience in process design at Monsanto, is in charge of our capstone design and economic evaluation courses. (Thanks in part to his contributions, our students have won AIChE national design contests several times.) **Marti Evans**, who worked in research and technical service in refining and petrochemicals for Shell, teaches as needed; currently, she is teaching a laboratory course that gives undergraduate students hands-on experience with advanced analytical instruments.

Greg McMillan is a principal consultant for TAC Worldwide Companies and is working on the next generation of advanced control in DeltaV for Emerson Process Management; he advises students on internships in control. **Terry Tolliver**, an ex-senior fellow at Monsanto/Solutia, teaches our control course. **Bob Heider** brings outstanding practical experience in designing, running, and controlling various chemical processes to our control laboratory course. Washington University ChE graduate **Nick Nissing**—who earned 11 U.S. patents while working for Procter & Gamble—currently is president of a consulting firm and teaches two senior-level classes on new-product development.

Robin Shepard teaches safety courses in the department. Starting in 2002 the AIChE design project began awarding a separate prize for the best applications of the principles of chemical engineering safety design, and Washington University students took home that prize three years in a row.

We also have a number of affiliate and research faculty (particularly, in this latter category, **Gregory S. Yablonsky**), who use their expertise to broaden the horizons of, and the availability of, diverse research projects for our graduate students.

STUDENTS AND ALUMNI

A generous, need-based scholarship program ensures that the best students can apply to SEAS, while a merit scholarship program enables the engineering school to attract students whose quality is second to none. It is our awesome responsibility to motivate this extremely talented group of young people. We accomplish this by taking our teaching duties very seriously, by having a strong advising and mentoring program, by offering abundant research opportunities, co-ops, and internships, and by allowing students to work on product development and capstone design projects with industry. Moreover, through exit interviews and correspondence, we monitor their careers and receive comments on the effectiveness of our programs.

Of all our graduates of distinction, perhaps the most unusual was Charlie Johnson, who, on his graduate-school application listed as his occupation: "Quarterback—St. Louis Football Cardinals." During the 1960s, Johnson tossed footballs during the fall semesters and took courses during the spring terms. He earned his M.S. ChE in 1963 and a D.Sc. in 1966.

On the graduate level, a strong chemical engineering core consisting of applied mathematics, transport phenomena, reaction engineering, and computational techniques is required of all students.

The diversity of the accomplishments of our alumni is astonishing. A few examples: **Julian Hill** (B.S. ChE '24) performed research and patented processes that made the manufacture of nylon possible. **Jim McKelvey** (M.S. ChE '47, Ph.D. ChE '50) was recognized *twice* with SEAS Alumni Achievement Awards, for his pioneering contributions to polymer processing and for his accomplishments as SEAS dean for 27 years. **Raymond W. Fahien** (B.S. ChE '47) taught at Iowa State University and the University of Florida and authored a textbook on fundamentals of transport phenomena. He was also former editor of *Chemical Engineering Education*.

The list goes on. **Bill Patient** (B.S. ChE '57) was CEO of Geon, one of the industry's major corporations. **Joe Boston** (B.S. ChE '59) was a cofounder of ASPENTECH. **Andrew Bursky** (B.S. ChE '78, M.S. ChE '78) is a successful businessman in the industry. **Mark Barteau** (B.S. ChE '75) is a leading figure in heterogeneous catalysis and chairman and distinguished professor at the University of Delaware. **Todd Przybycien** (B.S. ChE '84) is chairman of biomedical engineering at Carnegie Mellon University.

Of all our graduates of distinction, perhaps the most unusual was **Charlie Johnson**, who, on his graduate-school application listed as his occupation: "Quarterback—St. Louis Football Cardinals." During the 1960s, Johnson tossed footballs during the fall semesters and took courses during the spring terms. He earned his M.S. ChE in 1963 and a D.Sc. in 1966.

THE DEPARTMENT TODAY

The mission of our ChE department has always been to provide a first-rate chemical engineering education, to conduct exciting, world-class research and engage students at all levels in research activities, and to be of service to the community.

The department continues to provide a first-rate undergraduate education leading to the accredited B.S. ChE degree as well as the optional B.S. in Applied Science degree with emphasis in chemical engineering. The five-year B.S./M.S. program is increasingly popular, as is the control option leading to a combined ChE and Electrical and Systems Engineering degree. On the graduate level, a strong chemical engineering core consisting of applied mathematics, transport phenomena, reaction engineering, and computational techniques is required of all students.

The department currently ranks first at SEAS in research dollars from external research funding sources obtained per-year, per-faculty, and in overhead recovery generated per-faculty, per-year. The ChE department currently has about 40 full-time doctoral students and several postdoctoral research associates and research professors.

ChE AT WASHINGTON IN THE FUTURE

The ChE department's 1970 undergraduate curriculum was highly reflective of the "state of the science" at the time, and changed little until the year 2000. Now, however, with an overall objective to reflect chemical engineering's multiscale and multidisciplinary nature, our department is phasing in a revised curriculum. As can be seen in Table 1, basic science requirements now include biology (emphasizing cell structure and function). Other highlights of curriculum changes include: emphasizing multiscale concepts, including molecular level; stressing product design and development; and providing greater flexibility in customizing the curriculum. To this end, the core curriculum has been reduced to accommodate up to six additional elective courses in the desired area of concentration (*e.g.,* bioprocessing, environmental, materials, product development, or others as approved).

In addition, a strategic plan developed with the help of the Departmental Advisory Board calls for establishing a strong biomolecular presence in bioprocessing. This should allow us to capitalize more on the unique strengths of the university in biological sciences by appropriate expansion of our faculty.

Our ongoing goal of forming a natural link with both biomedical and environmental engineering begins with establishing modern, molecularly based chemical engineering principles. Using those as a basis for scaling up the pace of discoveries in life sciences, we aim to pursue products and processes that are environmentally desirable as well as being a foundation for comprehensive studies of the environment. The result should be an exciting environment for research and education.

Associate Professor John Gleaves explains his TAP (Temporal Analysis Products) system to visitors.

Our challenge for the future is to incorporate biomolecular engineering into our curriculum and research, thus strengthening our existing areas of excellence in environmental engineering, clean processing, aerosols, transport, reaction engineering, and materials. This biomolecular engineering initiative should also fill a major need in the St. Louis metropolitan area, which is strong in generating discoveries in life sciences but still lacks a focused center for either transferring these discoveries to useful products, energy, and processes, or for examining their environmental effects in a holistic manner.

TABLE 1
Revised ChE Core Curriculum

Basic Sciences	
(Biology, Chemistry, Mathematics, Physics)	**39**
Engineering Sciences	**12**
Chemical Engineering Core Courses	
Modern Technological Challenges (ChE 146A)	2
Analysis of Chem. Eng. Systems (ChE 351)	3
Thermodynamics (ChE 320)	3
Materials Science (ChE 325)	3
Molecular Transport Processes (ChE 359)	3
Transport I & II (ChE 367 or 366, 368)	6
Mass Transfer Operations (ChE 462)	3
Process Dynamics & Control (ChE 462)	3
Reaction Engineering (ChE 471)	3
Chemical Engineering Laboratory (ChE 373A)	4
New Product & Process Development (ChE 450)	3
Process and Product Design (ChE 478A)	3
Subtotal	**39**
Humanities & Social Science & Communications	18
Total ChE Core	**108**
Engineering Electives	
(6 courses from area of concentration)	18
Total	**126**

In his speech of Feb. 22, 1854, **William Greenleaf Eliot**, president of Eliot Seminary (which was later renamed Washington University) said:

> *"There is one view of the Washington Institute which I desire to keep particularly prominent—its practical character and tendencies. I hope to see the time when what we call the practical and scientific departments will stand in the foreground, to give character to all the rest. In some way or another, a practical and scientific direction must be given to all educational schemes of the present day . . . ."*

We in chemical engineering at Washington University are still striving to make Eliot's dream come true. Our theoretical advances are scientifically founded and motivated by the need to improve the quality of life through environmentally beneficial technology.

ACKNOWLEDGMENT

The authors thank **Barbara Carrow** for her technical assistance. ❒

C. Judson King

of UC Berkeley

John Prausnitz
University of California
Berkeley, CA

In the middle of the UC Berkeley campus, next to the Main Library, South Hall is the last surviving building from the original campus, founded about 135 years ago. A tiny tree-shaded appendix to this venerated classical building houses Berkeley's Center for Studies in Higher Education, directed by C. Judson King, former provost and senior vice president of academic affairs of the 10-campus University of California, and longtime professor of chemical engineering at Berkeley.

Jud came to Berkeley in 1963 as assistant professor of chemical engineering, following a doctoral degree from MIT and a subsequent short appointment as director of the MIT chemical engineering practice school station at what was then Esso (now Exxon) in New Jersey. His undergraduate degree is from Yale.

Starting with his MIT doctoral dissertation on gas absorption, Jud has devoted much of his professional career to separation processes. His teaching and research activities have been primarily concerned with separation of mixtures, with emphasis on liquid-liquid extraction and drying. As a consultant to Procter & Gamble, he contributed to the technology of making instant coffee. His lifelong activities in hiking and camping stimulated Jud's interest in the manufacture of freeze-dried foods (*e.g.*, turkey meat) to minimize the weight of his hiking backpack.

Jud is internationally known not only for his many research publications but also, and even more, for his acclaimed textbook *Separation Processes* (McGraw-Hill, second edition 1980) that is used in standard chemical engineering courses in the U.S. and abroad.

Born into an army family in Ft. Monmouth, NJ, in 1934, Jud moved about in the military world during his early years. He developed an interest in camping and mountaineering during that time, an avocation he has retained throughout his life. After high school in Alexandria (VA), higher education at Yale and MIT, and marriage to Jeanne (1957), Jud began his career at Berkeley in 1963.

While the concept of unit operations in chemical engineering is about 90 years old, when Jud started his professional career at Berkeley, about 40 years ago, the standard separation operations (distillation, extraction, absorption, etc.) were considered separate topics, each described by its own methodology. Through his research and teaching, and above all through

◀ ***Jud and John Prausnitz after receiving Berkeley-Citation diplomas at the College of Chemistry commencement in May 2004.***

▼ ***Jud (right) and Larry Genskow (of Procter & Gamble) at the International Drying Symposium in Kyoto (1984).***

his influential textbook, Jud showed that each of these separation operations is a special case of a unified technology that can be described by a general set of quantitative principles. Jud's book not only emphasizes the common aspects of various forms of separation technology; it also discusses convergence methods for computerized calculations, energy requirements, and rational criteria. First, for selecting an optimum separation method for a particular purpose, and second, for an optimized series of separation steps in an industrial chemical plant.

Jud's pioneering leadership in advancing the technology of separation processes is also indicated by the Separations Division of AIChE. He was the cofounder of that division 15 years ago.

A major part of Jud's research work has been concerned with freeze-drying—in particular, freeze-drying of foods, notably beverages such as coffee. A key problem in freeze-drying is retaining the volatile flavors while subliming ice. Further, it is extremely important to avoid collapse of the porous structure that results from sublimation; failure to prevent collapse makes it impossible to reconstitute the dried product by adding water. Similarly, for biological agents, collapse may cause the loss of biological activity. Jud and coworkers showed that collapse can be avoided by careful control of viscosity and by addition of suitable additives (excipients). In addition to foods, this work has also been of much help to guide freeze-drying of pharmaceuticals. In 1971, Jud published a book on the subject, *Freeze Drying of Foods* (CRC Press).

A second research area concerned extraction of carboxylic acids for recovery from dilute aqueous solutions. Such extraction is important not only for acetic acid but more recently, also for lactic acid that is used for making biodegradable polylactic acid. Jud and coworkers investigated the technology and economics of using suitable complexing agents (*e.g.*, amines) in suitable "inert" water-insoluble solvents. His research showed convincingly that the "inert" solvent plays a major role; in fact, it is *not* inert.

A third area of Jud's research has been directed at synthesis in plant design. Following the strong influence of the book *Transport Phenomena* by Bird, Stewart, and Lightfoot (published in 1960), chemical engineering research in the universities was primarily directed at analysis, at detailed microscopic descriptions of chemical and physical processes. During the 20-year period starting about 1965, Jud was one of the few academics who gave attention to the logic of plant design—to establishing rational criteria and methods that can make plant design more of a science than an art.

A popular and highly effective teacher, Jud supervised a large number of M.S. and Ph.D. theses. The names and present affiliations of his former Ph.D. students are given in Table 1 on the following page.

Within a few years after his arrival in Berkeley in 1963, it became clear that in addition to his fine abilities in teaching and research, Jud had truly extraordinary talents in administration. He was appointed vice-chair of the Department of Chemical Engineering in 1967 and became chair in 1972, where he remained for nine years. During that time, Berkeley's Department of Chemical Engineering grew remarkably in size and stature. Since Jud's chairmanship, the National Research Council has consistently rated the Berkeley ChE department within the top three in the United States.

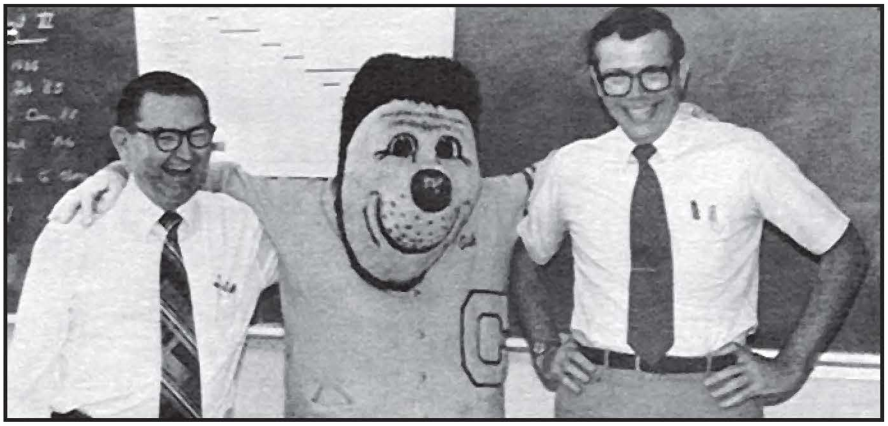
In 1981, Jud became dean of Berkeley's College of Chemistry, comprising two departments: chemistry and chemical engineering. Because the number of faculty and graduate students in chemistry is about three times the number in chemical engineering, Berkeley's world-famous Department of Chemistry has traditionally been the dominant part of the college. Jud was the first chemical engineer to become dean, a remarkable achievement because, all too often, academic chemists are reluctant to accept chemical engineers as equals. Because of his open fairness and his consistent good judgment, Jud was able to break that prejudice. In a sense, the election of chemical engineer Jud King in 1981 as dean of the College of Chemistry is analogous to the election of Catholic John Kennedy in 1960 as president of the United States.

Jud's achievements in chemical engineering research and education have been recognized by numerous awards, as shown in Table 2.

During his deanship, Jud led a successful effort to build Tan Hall, a major building (completed in 1997) for research laboratories in synthetic chemistry and chemical engineering, including biotechnology. In 1982, Jud established a College of Chemistry Development Office for obtaining much-needed financial support from alumni and corporations. While

TABLE 1
Ph.D. Graduates Supervised by C. Judson King

Keith Alexander	1983	Sr. VP, CH2M Hill, ret.; Joined Berkeley ChE Department as Executive Director, Product Development Program, 2005
Daniel R. Arenson	1988	Pfizer
Francisco J. Barns	1973	Former Rector, National Autonomous University of Mexico
Prabir K. Basu (with Scott Lynn)	1972	Searle
Carl P. Beitelshees (with Hugo Sephton)	1978	E.I. DuPont de Nemours
Richard J. Bellows	1972	Richard Bellows Advanced Energy Systems LLC
John L. Bomben	1981	SRI International
Robert R. Broekhuis (with Scott Lynn)	1995	Air Products
Charles H. Byers	1966	IsoPro International; living in Mexico
Kumar Chandrasekaran	1971	President, InSite Vision
Daniel Chinn	1999	Chevron Texaco
J. Peter Clark	1968	Consultant
Michael W. Clark	1967	Dow Chemical, ret.
Ian F. Davenport	1972	Structure and Strategy Specialist, Commonwealth Private Bank, Australia
Jonathan P. Earhart	1975	Hewlett-Packard
Tarric M. El-Sayed	1987	Clorox
Mark R. Etzel	1982	Professor, Food Science and Chemical & Biochemical Engineering, University of Wisconsin, Madison
Loree J. Fields (Poole)	1989	Woodward-Clyde Consultants
Howard L. Fong (with Hugo Sephton)	1975	Shell Development
Douglas D. Frey	1984	Professor, Chemical & Biochemical Engineering, University of Maryland, Baltimore County
Antonio A. Garcia	1988	Associate Professor, Bioengineering, Arizona State University
Terry M. Grant	1988	Weyerhaeuser
C. Gail Greenwald	1980	Chief Operating Officer, Caveo Technology
Robert D. Gunn	1967	Professor Emeritus, University of Wyoming; ret., St. George, UT
John P. Hecht	1999	Procter & Gamble
Scott M. Husson	1998	Associate Professor, Chemical & Biomolecular Engineering, Clemson University
Russell L. Jones	1975	Aventis CropScience
Dilip K. Joshi	1982	Pharmacia & Upjohn
Theo G. Kieckbusch	1978	Faculty of Chemical Engineering, Universidade Estadual de Campinas–UNICAMP, Brazil
Romesh Kumar (with Scott Lynn)	1972	Argonne National Laboratory
Patricia D. MacKenzie	1984	General Electric
Donald H. Mohr	1983	Chevron Texaco
S. Scott Moor	1995	Assistant Professor, Engineering, Indiana University–Purdue University, Fort Wayne
Curtis L. Munson	1985	Chevron Texaco
M. Abdel M. Omran	1972	Kuwait Industrial Park, Kuwait
Spyridon E. Papadakis	1987	Professor, Food Technology, Technical Educational Institution of Athens, Greece
N. Larry Ricker	1978	Professor, Chemical Engineering, University of Washington
William G. Rixey	1987	Associate Professor, Civil & Environmental Engineering, University of Houston
Gary T. Rochelle	1977	Professor, Chemical Engineering, University of Texas, Austin
Orville C. Sandall	1966	Professor, Chemical Engineering, University of California, Santa Barbara
John J. Senetar	1986	Amoco
John N. Starr	1991	EcoPLA Business Unit, Cargill
James H. Stocking	1974	Broken Arrow, OK
Janet A. Tamada	1988	Alexza Molecular Delivery
Rodney E. Thompson	1986	BioProcess Technology Consultants
Roger W. Thompson	1972	Max Kade Foundation
Lisa A. Tung	1993	Rohm and Haas
Ernesto Valdes-Krieg (With Hugo Sephton)	1975	IEGE, Mexico
David A. Wallack	1988	3M
Jack Zakarian	1979	Chevron Texaco



Jud (right) launching the Tan Hall Project in 1983, shown here with Project Manager Herb Fusfeld and Oski, the UC Berkeley football mascot.

such offices are now ubiquitous, 23 years ago it was a pioneering step to have such an office in a specific college in a state-supported institution. Jud correctly anticipated that in California (as elsewhere), state support for the university would seriously decline despite ever-increasing costs.

During his deanship, Jud started a new annual tradition. Every spring, the dean invites all college staff members to lunch to celebrate "Staff Appreciation Day." At this lunch, also attended by many faculty, the dean warmly thanks all the staff for their devoted service that is essential to the college's operation. He also recognizes individual staff members for outstanding service or for many years of service.

During Jud's six successful years as dean, the top Berkeley administration noticed his outstanding administrative abilities. As a result, in 1987, Jud was appointed Berkeley's provost for professional schools and colleges (Engineering, Law, Business, Chemistry, Social Welfare, Environmental Design, Natural Resources, Education, Optometry, Public Health, Public Policy, Journalism, and Library and Information Studies), a position directly under the Berkeley chancellor. One of his major tasks was to help define the role of agriculture on the Berkeley campus and to modernize agricultural sciences.

In 1994, the president of the University of California chose Jud to serve as vice provost for research, and in 1996 selected him to be his right-hand man as provost and senior vice president for academic affairs for the entire university system, including Berkeley, UCLA, UC Davis, UC Santa Barbara, and six more. In addition to many other duties, Jud had responsibility of programmatic oversight for the Department of Energy National Laboratories at Berkeley, Livermore, and Los Alamos.

As the university's provost, Jud had many diplomatic challenges, including relations with the university's often volatile Board of Regents concerning affirmative action with respect to student admissions and recruiting of faculty and staff. Further, it was his task to provide academic planning for how the university could accommodate an expanding population of college-bound Californians in the face of decreasing financial resources.

Because the president of the university is much occupied with the university regents, the governor, and the state Legislature in Sacramento, as well as with the federal government in Washington, with alumni, industrialists, labor unions, etc., it was Jud who had to "mind the store," to take care of the university's daily operations. Jud retired from this awesome administrative position in 2004.

TABLE 2
Honors and Awards

- **The Electrochemical Society Lecture**, The Electrochemical Society, 1998.
- **Outstanding Alumnus,** Yale Science and Engineering Association, Yale University, 1998.
- **Award in Separations Science and Technology,** American Chemical Society, 1997.
- **Centennial Medallion,** American Society for Engineering Education, 1993.
- **Fellow,** American Association for the Advancement of Science, 1993.
- **Clarence G. Gerhold Award**, Separations Division, American Institute of Chemical Engineers, 1992.
- **Warren K. Lewis Award**, American Institute of Chemical Engineers, 1990.
- **Mac Pruitt Award,** Council for Chemical Research, 1990.
- **Award for Excellence in Drying Research**, International Drying Symposium, 1990.
- **Ninth Centennial Lecturer in Chemical Engineering,** University of Bologna, 1988.
- **Fellow,** American Institute of Chemical Engineers, 1983.
- National Academy of Engineering, 1981.
- **George Westinghouse Award,** American Society for Engineering Education, 1978.
- **William H. Walker Award,** American Institute of Chemical Engineers, 1976.
- **Food, Pharmaceutical and Bioengineering Division Award**, American Institute of Chemical Engineers, 1975.
- **Best Paper Award,** 15th National Heat Transfer Conference (with H.L. Fong and H.H. Sephton), 1975.
- **25th Annual Institute Lecturer**, American Institute of Chemical Engineers, 1973.
- Tau Beta Pi
- Sigma Xi

Jud's remarkable administrative skills follow from his smiling, soft-spoken manner and from his uncompromising, conscientious sense of fairness, responsibility, and punctuality. Shortly after his arrival in Berkeley, these skills became evident to his colleagues who admired Jud's calm efficiency in organizing his classes and research program. Soon after his arrival, following an insightful and concise presentation Jud made at a departmental faculty meeting, a

◄ *Jud and wife Jeanne (1995).*

Jud in his role as scoutmaster (circa 1979). ►

Jud and his daughter Liz at Timothy Dwight College (Yale) at Liz's graduation in 1981. Both Jud and Liz were members of TD College during their Yale years. ▼

senior professor in the department remarked, "This fellow is amazing. He could run General Motors."

Whether with students, colleagues, secretaries, carpenters, or CEOs of major corporations—in short, with anyone—Jud has a gift for attentive listening. His role as administrator is to be helpful rather than obstructive. His decisions are always well-considered; they are clear, unambiguous, and expressed with gracious diplomatic sensitivity. Everyone may not agree with a particular decision but it is always received with respect and without rancor. Jud's firmness is always accompanied with a friendly twinkle, often enhanced by light humor. No one ever gets angry with Jud, nor does he ever show anger: He is always calm and considerate, never raising his voice. At heated faculty meetings it would be instructive to put a pH meter in his stomach to determine his real feelings.

Jud and Jeanne King have three (now grown) children: Mary Elizabeth, Cary, and Catherine. Since 1969, Jud and Jeanne have lived high in the Kensington hills, in a house overlooking Tilden Park. They are enthusiastic hikers all over California, especially in the Sierra Nevada Mountains (where they have a summer residence at Mammoth Lakes) and on the coast, between Jenner and Mendocino (where they have a weekend home in The Sea Ranch near Gualala).

For many years, Jud was active in Boy Scouts, serving as scoutmaster of a local Boy Scout troop. He has led dozens of overnight scouting hikes in the mountains, canyons, and parks of California. When asked if he ever had disciplinary problems with his boys, Jud replied, "No, the boys are no trouble. But sometimes I had problems with accompanying dads."

A perennial problem of such hikes is avoiding poison oak. Following unintended exposure to poison oak, Jud recommends soaking 15 minutes in a full bathtub with one cup of Clorox added to the bath water.

Now, as director of Berkeley's Center for Studies in Higher Education, Jud is using his extensive university experience first, to identify some major problems facing higher education in California (and elsewhere). And second, to stimulate research toward solving such problems. Topics that reflect his particular concerns include the university's role in maintaining and promoting innovative technology, methods for sustaining a large research-oriented university in the face of perennial financial shortages, and the role of new technology to advance and facilitate scholarly communication.

Jud's distinguished career as a chemical engineering educator has blossomed toward concerns with higher education in general. For the last 20 years, Jud's work has been directed toward answering a key question: Today and tomorrow, what is the proper function of a university in the world, in the U.S., in California? While many academics are working on this question, Jud is particularly well-qualified to do so—not only because of his long experience in university administration, but also because of his chemical engineering background that favors versatility, respect for new ideas, goal-orientation, and a faith that good science can lead to useful results.

In engineering and in public service, Jud enjoys a stellar reputation. Whenever President Bush needs to replace a member of his administration, Jud King would be an excellent candidate. ❐

INSTANT MESSAGING
Expanding Your Office Hours

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Over the past 10 years we have witnessed amazing changes in communication, specifically regarding the rise of the Internet in everyday communications. All professors, new and old, know about e-mail, and many know how to access journal articles via electronic means. But faculty over the age of 35 may not know about instant messaging (IM). On the other hand, anyone under the age of 25 may not know of any other means of communication (such as how to write a letter and send it via the postal service). We offer below our experiences with IM as a means to "keep in touch with students" and expand our availability.

BACKGROUND

For those unfamiliar with the concept, instant messaging is different from e-mail in that the messaging is one-on-one and occurs in real time. For example, a graduate student from Italy used an instant messaging service to dialog with her sister daily while she was working in a laboratory in Boston. She would type a question, and approximately two minutes later her sister would reply. It is very similar to having a written conversation where a piece of paper is passed between two parties.

In IM, the questions and replies happen in real time. All IM services allow users to have a "friends list" of other IM users, and the service polls these friends in real time to let the user know whether or not they are "signed in" (online). Once signed in, the user can send a message to any other online user or receive a message from any user. Once a connection is established, a separate dialog box appears, and the two parties then send messages back and forth to each other. There is no limitation as to location; IM helps people keep in touch across town or across the planet, and has been used in such exotic locales as Antarctica and the Space Station.

► *The New Professor's Experience* ◄

As a first-year professor teaching my first course, I (DB) was looking for ways to relate to students and provide them with as many means of getting help as they needed. The class was an introductory thermodynamics course in chemical engineering with 28 students and was a mix of second- and third-year students, the vast majority of whom were native English speakers. The mixed nature of the course meant that students were coming with different experience levels as well as with wildly different schedules, which made finding times for traditional office hours challenging.

One of my TAs for the course, a seasoned graduate student and a veteran TA, mentioned that he often held "virtual office hours"—office hours where he had an online presence via an instant messaging service, such as America Online's Instant Messenger (AOL AIM). He would often have these online sessions in the evenings, when students were likely to be tackling assignments and required guidance or had questions about problem sets. I was intrigued, and decided that I would also try having an online presence for students. Since assignments for the class were due Mondays and Thursdays, I decided to have a session on Sunday evening from 9 p.m. to 10 p.m. in order to try and catch last-minute questions for assignments on Mondays. My TA would have another session during the week to catch questions for the Thursday assignment set.

I had some previous experience with instant messaging. It had become popular when I was in college in the late '90s—but as a communication tool among friends, not as a method of instruction nor as a means of enhancing student-instructor contact hours. I had a personal instant messaging account,

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While there are limitations to the forum, such as the lack of robust mathematical notation . . . as new technology becomes available, many of the limitations will disappear . . . . As these technologies become more commonplace, we can expect them to be used in the learning environment. Right now, we're just at the beginning of this technological explosion.

but created a new one for the sole purpose of the class. I knew that my TA had had success with his online sessions, but he was a graduate student and closer in age and experiences to the students than I was. I had no idea if the students would actually feel comfortable enough to contact a professor in this manner.

I sat down for my first session on a Sunday evening, and my wife was convinced that I would be sitting there for an hour staring at a blank screen. How wrong she was!

Within seconds of signing on, I received my first message and my first question. Other students quickly followed, and within a few minutes, my screen had erupted in a flurry of new windows, each bearing a new question from a different student or group of students working together. I estimated that I had at least nine or 10 simultaneous conversations occurring in those first few minutes. To be honest, I wasn't prepared for that response, and my wife was amazed. She actually helped me get through that first evening by watching my screen and letting me know in what order the questions arrived. That enabled me to prioritize or tell people to hold on for a minute or two while I answered another student's question. The students were very patient, and very respectful of the time limit I had set, and before I knew it, the hour was up. I was drained and had cramped fingers from trying to type so fast, but I knew that I had hit upon something that the students responded to.

After that first session, I coordinated with my TA so that we were often on at the same time, enabling us to pass students back and forth between us and reducing the load on ourselves as well as speeding up the time it took for any one student to get a question answered. That first night was my heaviest load, but the students took advantage of my availability throughout the remainder of the semester.

In trying to gauge the success or impact of the online office hours, I asked the students to fill out an anonymous survey at the end of the semester, asking them about office hours in general. Out of 28 students in the class, I received 22 responses. When asked their office hours habits, the breakdown was as follows:

Online Only	*9%*	*2 responses*
Online and Traditional	*50%*	*11 responses*
Traditional Only	*23%*	*5 responses*
Neither	*18%*	*4 responses*

So, nearly 60% of the class took advantage of my online presence, either exclusively or as a supplement to my regular presence in the office during the day. Of those students that took advantage of the online hours, 77% found it an effective way of getting their questions answered, while 23% did not.

When asked about the best feature of online office hours, nearly all students responded that it was my extra availability, as well as the convenience of being available at a time when they were likely to be working on problems. When asked about what they liked the least with regard to online office hours, again the response was nearly unanimous: the limitations of the forum.

I can understand these limitations well. While it is an excellent forum for discussing theoretical or conceptual aspects of the course or for having a personal conversation, the instant messaging format was not the best medium for conveying technical aspects of the course. Mathematical symbolism, for example, was particularly difficult to convey, as there was no easy or convenient way to write out an integral or a differential equation. The students and I often resorted to a sort of crude shorthand for mathematical notation which, while effective, was not ideal. For example, in a discussion involving fugacity, and which form of a particular equation to use, I would type

fi (hat) = yi * fi
Where fi = phi (hat) (i) * P

which the student would have to correctly interpret as

$$\hat{f}_i = y_i f_i$$

where

$$f_i = \hat{\phi}_i P$$

So, questions dealing with a particular equation, or trying to guide a student by looking at the form of an equation, could be awkward to answer in an IM window. The students were generally happy, however, to spend a little extra time typing and interpreting if it meant the difference between getting a question answered or spending a fruitless evening confused and working in the wrong direction.

The last question I asked them was whether the availability of online office hours made them more or less likely to attend traditional office hours. I only had 13 responses to this question, but it was interesting to me that while the majority said it made no difference (8 responses, 62%), the remainder (5 responses, 38%) said it made them *less* likely to attend regular office hours.

In the end, I found the experience to be a rewarding one. The students would often joke around a bit more online than they might in person, and I had some good conversations with students about their futures and concerns that had little to do with the class or a problem set. Would this have happened in person? I'm uncertain; but, if those conversations helped students, then it was worthwhile. Given that a majority of students in the class took advantage of the additional contact hours, and that a majority of them found the experience useful, it is something that I planned to continue in my future course offerings.

Indeed, as of this writing, I have just completed another semester of teaching the undergraduate thermodynamics course, and my experience this time closely mirrored my original observations. Students were pleased to have the extra hours available to them, and took advantage of those hours on a regular basis.

► *The Old Professor's Experience* ◄

I (RJW: 20-plus years experience) first gained an awareness of instant messaging in January 2004 at a faculty recruiting dinner. The new faculty (DB) was talking about how well instant messaging was working for him running one of his office hours from his home on Sunday nights. The idea intrigued me since, for whatever reasons, students do not come to my office during my office hours.

After struggling with learning the ropes of IM (it took a few hours to download the software, figure out a user name, and figure out how to add "my friends"), I was ready for my first online session by mid-semester in February, and decided to try 8 p.m. Sunday night from my home. I had previously announced to the class that online office hours would be held that coming Sunday.

Within minutes, three students contacted me via instant messaging. Each had his/her own dialog box. The questions and messages were a little confusing to me at first. When one of them opened with a message similar to "How was your weekend?" my reply was a paragraph long, detailing a trip to New Hampshire, and took a full 15 minutes to type out. Meanwhile, other students were waiting for their replies. I quickly learned to cut my replies down to one sentence—I later realized that for "small talk" the students expected about a one-sentence reply.

The second surprise was how few technical questions I received. I was expecting questions related to the latest homework. Instead, only about one in every three or four questions was of this nature. I recall one question that was iterative in nature. The student who asked wasn't familiar with Excel Solver, so I was able to make up a quick spreadsheet example demonstrating such, and sent it via IM to the student.

What other students wrote was quite complex. Their questions and dialog ranged from jokes to personal family situations to serious self-doubt. They related much more to me than if they were sitting across from me in my office during a regular office appointment. I'd like to think that some of my replies made a difference.

Maybe, because I am so technically oriented, I lose awareness of students' personal needs, and when I sit across the desk facing students, I am perceived as their parent, or as an "old geezer," and therefore they are reluctant to share personal problems. Also, I must confess that I can be impatient when the point of their question isn't brought up immediately. I am sure the students sense this body language in a face-to-face meeting—but with IM they cannot sense my hidden impatience. Using instant messaging brings me to their stage where, despite the age difference, we are both the same—someone who is online conversing. I am treated as a peer.

I was very pleased to have connected with this class in this manner. I continued IM for a summer course, but I didn't connect as well as I did in the spring semester. I suspect that my hours (Sunday night again) just didn't meet the students' needs when they were online. Also they were two years younger (sophomores) and I represented their first experience with an "old" professor—I'd wager they probably didn't believe that I knew how to use IM!

CONCLUSIONS

In conclusion, adding more hours of contact time via a nontraditional method such as IM has the potential to facilitate student-instructor interactions outside of the normal classroom context. It also may help reach those students whose schedules don't allow them to regularly attend face-to-face office hours, or those students who, for whatever reason, aren't comfortable with an in-person interaction.

Because the concept itself is relatively straightforward, and the required software is essentially free, even a faculty member with limited computing skills can take advantage of this type of forum with just a little practice. Online office hours may not be for everyone, however. Both of the classes that are discussed in this article were relatively small, ranging from 15 to 30 students. How a lone faculty member would fare with 60 students (in a large class) or 200 students (in an intro or seminar-style class) is unknown to the authors at this point. With that many students, even a fraction of them online and asking questions at once could be overwhelming. With the proper ground rules, scheduling, and some assistance from TAs, however, we believe that this method is extendable to larger class sizes.

Additionally, while there are limitations to the forum, such as the lack of robust mathematical notation mentioned above, as new technology becomes available, many of the limitations will disappear. For example, improved handwriting-recognition software will allow for expression of mathematical notation that can be exchanged between users, and advances in voice and video compression will allow for real-time virtual interactions that won't be limited to the typewritten word. As these technologies become more commonplace, we can expect them to be used in the learning environment. Right now, we're just at the beginning of this technological explosion. ❐

A COURSE-LEVEL STRATEGY FOR CONTINUOUS IMPROVEMENT

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The ABET Engineering Criteria (EC)[1] is generating an unprecedented sensitivity to assessment and tracking of student performance in engineering learning.[2,3] This flurry of activity has many faculty and departments searching for and inventing various models for assessing student performance as well as for establishing a record of those assessments and ultimately applying them within a process for continuous improvement.[4,5] In this context, continuous improvement means making changes to the course/curriculum to quantitatively improve student performance against outcomes. As such, many of the recently introduced continuous-improvement activities can be broadly categorized as outcomes-based assessment[6,7] and are being driven by the ABET defined Criteria 3.[1] And, while ABET did not invent outcomes-based assessment, the accreditation organization has clearly defined the outcomes-based movement in U.S. four-year engineering programs.

One key aspect within this trend is to find the most effective assessment tools as well as the ones with economical bookkeeping strategies. While the literature offers far too many strategies to be cited here, among them are the following notable examples that illustrate the range of approaches. These include a skills assessment worksheet,[8] application of quality-control theory,[9,10] the use of questionnaires,[11,12] and a grading matrix.[13]

Shor and Robson's *Student Centered Control Model* requires course-level ABET-based accounting and suggests a "scoring guides" practice that tracks ABET skills performance.[9] McCreanor demonstrated a college-level approach to tracking a specific outcome—ABET Criterion 3b, the ability to design and conduct experiments.[8] McCreanor's approach relies on a "standardized" skill assessment worksheet distributed to select courses across all departments and centrally assessed. Mandayam, *et al.*, has implemented a curriculum-wide assessment tool called *X-files*, which captures student assessments across the curriculum.[14] On a course-level, Terenzini, *et al.*, demonstrated a student-based questionnaire used to gather course-level student responses and feedback.[11]

Shor and Robson's[9] work suggests that objective (outcomes-based) scores be given at the course level rather than an overall score, but focuses mainly on using the outcome results in the context of a control loop. Winter[13] provides details regarding his course-level accounting practice that tracks student achievement against "tasks" on exams. Winter links tasks to objectives such as ". . . obtaining the velocity field," or ". . . conservation of linear momentum," but does not map objectives to skill-based proficiencies, *e.g.*, ABET outcomes. His accounting practice scores exams according to task, thereby enabling him to identify strengths and weaknesses against specific, topical (task) areas of the course. Terenzini, *et al.*, use student self-assessment rather than objective measures of proficiency such as test or project scores. All report their results in a descriptive and qualitative manner.

The present study uses some of these concepts[9,13] yet illustrates direct connectivity to skills-based (ABET) outcomes. It also details the course-level practices and presents quantitative results from a case study.

Prior to ABET Engineering Criteria, most faculty in engineering colleges designed their courses in what will be re-

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ferred to here as the *requirements domain*. This form of course design specifies requirements (such as homework, exams, attendance, projects, etc.) and places a value on each, thereby establishing what we generally refer to as the *course breakdown* or requirement breakdown (r_i). For example, a lecture-based course in stage-wise separation might be broken down such that homework is 15%, projects are 20%, attendance and participation are 5%, a portfolio is 5%, and exams are 55%, of the grade. In this way, the traditional requirements domain scorecard is produced by summing individual assignment scores for each requirement, and computing the overall score by summing the weighted average of the scores for each requirement.* This form of breakdown is both simple for the instructor and tangible to the students. The requirements may be further categorized or mapped to a pedagogical device such as a classroom activity, team assignment, in-class assessment, etc. (see insert in Figure 1).

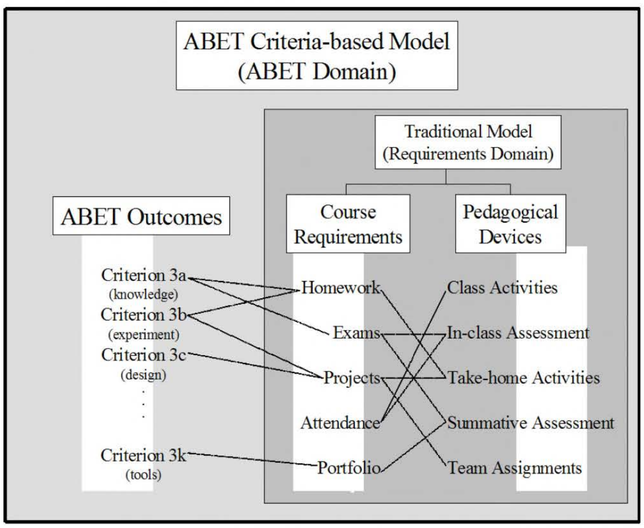

***Figure 1.** Framework for the ABET criteria-based model.*

* $$\hat{S}^i = \sum_{j}^{n_a^i} s_j^i \Big/ \sum_{j}^{n_a^i} p_j^i, \quad \hat{S} = \sum_{i}^{n_r} r_i \hat{S}^i$$

where $\hat{S}^i$ is the total normalized score for the i^{th} requirement, s_j^i are the scores for the j^{th} assignment within the i^{th} requirement, p_j^i are the possible scores for the j^{th} assignment within the i^{th} requirements, and n_a^i is the number of assignments for the i^{th} requirement, $\hat{S}$ is the normalized score, r_i is the weighting factor, and n_r is the number of requirements for the course.

To satisfy ABET, however, it is not enough to provide this form of breakdown alone. In the ABET environment the following questions must be answered: *How did students perform against Criterion 3x? What changes were made to improve student outcomes as measured against criteria . . . ? What strategy is being used to ensure continuous improvement?*

These questions cannot easily or convincingly be answered in the traditional domain. The traditional requirements must somehow be further subdivided to reflect the ABET Criterion 3 categories[1] and then mapped to the desired outcome (Figure 1). In this way, the traditional approach is not simply encompassed within the ABET model, but must be extended to adapt to the outcomes-based assessment protocol. This new way of distributing course requirements is the topic of the present experiment, which offers one faculty's experience in tracking outcomes-based, course-level assessment information. The experiment also demonstrates how such can be used to objectively alter course content, track and hopefully influence student performance, and at the same time, maintain a quantitative record for ABET reviews. The goal in the end is course-level continuous improvement that enhances student learning and the overall quality of the educational experience.

OUTCOMES-BASED METHODOLOGY

The following outcomes-based strategy, which connects course requirements (such as exams and homework) to outcomes (such as ability to apply mathematics and science), was applied to various learning environments, including: two required lecture-based unit-operations courses, a required senior-level chemical engineering laboratory, a required senior-level departmental technical seminar, and a nontraditional interdisciplinary technical elective (see Table 1). First, the catalog description of the course from which content-based learning objectives were developed was consulted. The appropriate ABET EC Criterion 3 were selected and a set of outcomes were written that map the content-based objectives to the ABET criteria. The course requirements were then established and mapped to the outcomes so that each requirement would have assessment standards linked to one or more of the selected ABET Criterion 3 outcomes. This establishes what will be referred to here as the *assessment map*. An example assessment map for Transfer

TABLE 1
Test-Beds for Course-Level ABET Strategy

Course	*Title*	*Pedagogy*	*Subject*	*Level*	*Credit Hrs*
CHE 3110	Transfer Science I	Lecture	Momentum and heat transfer	Junior	4
CHE 3120	Transfer Science II	Lecture	Stage-wise separations	Junior	3
CHE 4240	Chemical Engineering Laboratory	Lab	Unit operations	Senior	2
CHE 4810	Developing Areas in Chemical Engineering	Seminar	Miscellaneous	Senior	1
CHE 4470	Ceramic Materials Engineering	Lecture/Lab	Materials engineering	Junior/Senior	3

Science II, a junior-level required stage-wise separations course, is given in Table 2.

With each requirement mapped to one or more of the select ABET Criterion 3 it is possible to explicitly track performance, assuming that the requirements are adequately designed to demonstrate the desired outcomes. In this new *outcomes domain*, the requirements must contain elements of assessment that map to the criteria. For example, since exams are mapped to communication (ABET Criterion 3g), student exams must include elements of communication and likewise be appropriately assessed and be assigned a communication score. A simple approach is to include a free-writing problem and score it both for technical content and written articulation. Similarly, since homework is mapped to use of engineering tools (ABET Criterion 3k), at least a portion of homework must involve the use of tools such as programming software, spreadsheets, process simulators, the Internet, etc., and be appropriately assessed for mastery of this element.

It is important to note that assessment is a distributed process in which all components of the grade are related to outcomes and are assessed individually. Exam performance on its own does not demonstrate that a given criterion is met. Rather, a combination of requirements and assessment approaches must be used to provide a valid assessment. Furthermore, for the present accounting strategy to be broadly applicable to program-level quality improvement beyond the classroom, persons other than the instructor must be involved in the process, *i.e.,* an external reviewer for a final project or a colleague who assesses or writes an exam problem, etc.

Finally, skills assessment against a learning model, *i.e.*, *Bloom's Taxonomy*,[15] can also be addressed in this context, although this experiment did not include this higher level of assessment. Table 3 illustrates the bookkeeping required to track performance by both requirement and criterion.

IMPLEMENTATION

The methodology described here was implemented in five chemical engineering courses over a three-year period to test general suitability for application across the curriculum (see Table 1). A single junior-level required course in stage-wise separations was used as a case study to illustrate the process of implementation and feedback at the course level. The results are later discussed in the broader context of laboratory and elective courses and, finally, curriculum-level feedback.

Course description

CHE 3120, Transfer Science II, is a junior-level required course in stage-wise separation processes. When broken down in the traditional requirements domain, 55% of the grade will come from exams, 20% from projects, 15% from homework, and 5% each for attendance and a portfolio. Five midterm exams and a final are given. The project varies from year to year but typically involves using or developing a process simulation.

Breaking the course requirements into ABET criteria

Traditionally an instructor will assign a problem and grade it according to a rubric that establishes the correctness of the solution and will then assign credit for the problem—a score. This score becomes one of many that will be accumulated to make up the elements of the grade. In the outcomes domain the same problem must be analyzed so as to assess for select ABET Criterion 3. For example, consider a typical homework problem in stage-wise separations:

> *Specify the number of ideal equilibrium stages required to separate a 40 mole % methanol in water stream at its bubble point into a distillate containing not more than 5 mole % water and a waste stream not containing more than 2 mole % methanol.*

The question itself need not be altered in the new outcomes environment, but how we view assessment must be changed. This problem clearly contains a variety of ABET Criterion 3 elements that can be individually assessed. First, it contains elements of design (ABET criterion 3c), regardless of the fact that the word *design* does not appear in it. In addition, it requires that the student apply knowledge of science (Criterion 3a), *i.e.,* students will have to select appropriate models for the phase equilibrium. Students must select a methodology to solve the problem (Criterion 3e) and to formulate and solve engineering problems. Is a material balance required? Is a heat balance required? What are the governing equations relating the material, heat, and equilibrium relationships? The problem must be solved, requiring application of mathematics (again, Criterion 3a). The instructor may also specify that the problem be solved using a process simulator or that a mathematical model be developed, including elements of Criterion 3k—use of modern engineering tools. Finally, students must assemble their results into a format that can be understood (Criterion 3g, communications). So, a *simple* problem that chemical engineering faculty have been assigning for decades is rich with outcomes-based information—only, however, if it is subdivided and scored according to the outcomes criteria. A similar approach was used for exams, the project, and other assigned coursework.

TABLE 2
Assessment Map for a Junior-Level Stage-Wise Separations Course

Requirement	*Criterion 3a Knowledge*	*Criterion 3c Design*	*Criterion 3e Formulation*	*Criterion 3g Communication*	*Criterion 3k Tools*
Attendance				X	
Project		X	X	X	X
Exams	X	X	X	X	X
Homework	X	X	X	X	X
Portfolio				X	

TABLE 3
Outcomes-Domain Bookkeeping Approach

Assignment No.	for Requirement i — ABET Criteria					Overall Assignment Score
	C_1	C_2	C_3	...	C_k	
a_1	S^i_{11}	S^i_{12}	S^i_{13}	...	S^i_{1k}	S^i_1
a_2	S^i_{21}	S^i_{22}	S^i_{23}	...	S^i_{2k}	S^i_1
a_3	S^i_{31}	S^i_{32}	S^i_{33}	...	S^i_{3k}	S^i_1
a_j	S^i_{j1}	S^i_{j2}	S^i_{j3}	...	S^i_{jk}	S^i_j
Overall Criterion Score	s^i_1	s^i_2	s^i_3	...	s^i_k	

$$s^i_k = \sum_j^{n^i_{a_k}} S^i_{jk}$$

$$S^i_j = \sum_k^{n^i_{c_j}} S^i_{jk}$$

Where the S^i_{jk} are the scores for the k[th] outcome criteria of the j[th] assignment of the i[th] requirement; the s^i_k are the criteria score sums for the k[th] criteria of the i[th] requirement; and the S^i_j are the assignment sums for the j[th] assignment of the i[th] requirement.

TABLE 4
ABET Scorecard

Student	ABET Criteria					Overall Score
	3a	3c	3e	3g	3k	
#1	72.3	65.5	72.6	88.5	94.5	76.3
#2	90.0	89.5	90.2	95.9	89.9	91.1
#3	74.0	67.9	74.4	93.2	90.4	78.3
#N	62.4	53.6	62.9	90.0	86.6	68.7

$$\hat{s}_k = \frac{\sum_i^{n_r} \sum_j^{n^i_{a_k}} S^i_{jk}}{\sum_i^{n_r} \sum_j^{n^i_{a_k}} p^i_{jk}}$$

$$\hat{S} = \sum_k^{n_c} a_k \hat{s}_k$$

Where $\hat{s}_k$ is the overall normalized score for the individual ABET criterion 3 (one of the a-k), p^i_{jk} are the possible points for requirement i, assignment j and criterion k and n^i_{ak} and n^i_c are the number of assignments for requirement i with criterion k and the number of criteria for requirement i respectively.

TABLE 5
Comparison of Requirements Breakdown and Outcomes-Based Breakdown for a Junior-Level Stage-Wise Separations Course

Requirement	Requirement Breakdown	3a knowledge	3c design	3e formulation	3g comm.	3k tools
Exams	55%	43.9%	15.1%	35.2%	4.7%	1%
Projects	20%	28.9%		20.5%	18.9%	31.6%
Homework	15%	37.7%	6.8%	36.5%	19.1%	
Participation	5%				100.0%	
Portfolio	5%				100.0%	
ABET Breakdown	100%	35.6%	9.4%	29%	19.2%	6.9%

$$a_k \qquad a^i_k$$

Where a^i_k are the breakdown for the i[th] requirement associated with the k[th] criterion and a_k is the ABET breakdown for the k[th] ABET criterion.

Another noteworthy point is that the assessment of an assignment is only as good as the assessment protocol used. Within the context of the proposed course-level strategy for use of assessment information for continuous improvement, the faculty are responsible for ensuring meaningful assessment of student proficiencies. This might include projects, oral presentations, observation, peer input, and, yes, even exam scores. Further discussion on this subject can be found in the literature and is outside the scope of this paper.

Doing the bookkeeping

The accounting practice is simple: With each requirement (i) broken into assignments (j) and each assignment broken into elements of the criteria (k), a score for each assignment element (S^i_{jk}) within a requirement is given, rather than just an overall assignment score (see Table 3). These outcomes-based (criteria-based) requirement subscores can then be summed by assignment (across rows) to give overall assignment scores S^i_j or by criteria (down columns) to give overall outcomes-based scores s^i_k for that requirement. Summing the requirement subscores by assignment is equivalent to a traditional approach in which a single score is given for a single assignment without attaching performance to a particular outcome. Summing the assignment subscores by outcome (criteria), however, provides the outcomes-based distributed information that we are seeking in this approach. In this way, an *outcomes-based scorecard* is generated, thus creating an explicit record of student performance against stated ABET outcomes (Table 4).

A strategy for computing and tracking the outcomes-based breakdown on an ongoing basis was also devised for formative assessment purposes. At any point in the semester the outcomes breakdowns by requirement (a^i_k) or overall (a_k) can be computed. By summing the possible points by criterion within a requirement and normalizing by the total possible points, the normalized-outcomes criteria breakdown (a_k) within a requirement is determined. By further forming the sum of the requirement-weighted normalized criteria breakdown, the overall outcomes-based criteria breakdowns can be computed. This produces the outcomes-based breakdowns (Table 5), which can be computed at any time, including term-end.

Establishing proficiency levels

How should proficiency levels be established? As with any grading system, scores (Table 4) represent a proficiency level measured against some standard, *i.e.*, a known correct problem solution, an accepted format for a report, the expected outcome of an experiment, or an anticipated level of team participation. At this time, assessments (*i.e.*, exams, projects, homework, etc.) are deliberately designed to evaluate student learning at various levels, but are not tied to a learning framework such as *Bloom's Taxonomy*. Traditional guidelines were used in accordance with the instructor's judgment concerning the level of difficulty and content of each assignment, *i.e.*, average passing scores for each outcome (criteria) were taken to be 60%, with each grade level generally at 10% increments. Admittedly, one of the next challenges will be to tie assignments to "domains of learning," for example, as defined by Bloom.[15] This would provide a more defendable basis upon which to make competency decisions.

Finally, the distributed outcomes-based information for each students' performance (Table 4) provides a unique dataset that forms the basis for a new way of grading. Since outcomes are based on ABET criteria that state that "students will demonstrate" proficiency in a specific topic, a passing grade (for example) should no longer be tied to an overall score alone. Proficiency levels in each outcome area should be defined and a grading protocol established that incorporates an outcomes-based strategy. This, however, was beyond the scope of the present study.

Planning so the process is manageable . . . tips for implementing at the course level

Preplanning a course in this way can be extremely difficult, time consuming, and some might even say "impossible." The following guidelines, however, were used to make it more achievable as the result of lessons learned in this pilot study.

As usual, the requirements domain was fixed prior to teaching the course, while only a rough idea of the outcomes breakdown was established *a priori* as a target. Analyzing every assignment, in the detail described above, is a daunting task, however. When implementing such a strategy, a week-by-week approach works well: Identify the homework to be assigned for a given week; review the problems one-by-one; break them into outcomes criteria and grade them accordingly once students have completed them. If a teaching assistant is going to do the grading, some *calibration* may be required. Examples may be necessary to train the grader to recognize the outcomes elements of an assignment and to grade in the outcomes domain.

DISCUSSION

Results of implementation

The results of three semesters (three years) of data from CHE 3120 are discussed. The course was successively taught in 2001, 2002, and 2003 by the same instructor (the author) and the methodology described herein applied. Three performance metrics were used to study student and course outcomes:

- *Outcomes breakdown (Figure 2)*
- *Class-average performance against Criteria 3a, 3c, 3e, 3g, and 3k and class-average term-end performance against requirements as a function of time (Figures 3a and 3b, respectively)*
- *Class-average term-end performance against the ABET criteria (the outcomes), (Figure 4)*

The net outcomes breakdown at the end of each term is illustrated in Figure 2. This figure represents the portion of the overall coursework that could be attributed to each of the five ABET criteria emphasized in the course. During the first two semesters (2001 and 2002), no conscious effort was made to alter the course content to adjust the outcomes breakdown. Since the new methodology was being developed, these first two semesters were used as a baseline to establish nominal course performance without significant intervention to alter the outcomes breakdown. During these two semesters the knowledge content was about 37%, the formulation content 32%, the design content 6%, the communications content 18%, and the tools content 7%. During the third semester (2003), however, an effort was made so that roughly 15% of the course content was design related, 10% tools (3k), and 10% communication, with the remainder split between knowledge (3a) 35%, and formulation (3e) 30%. This was not done to *balance* the emphasis, but rather to reflect this instructor's opinion that the particular course content should have a more significant design aspect and a more appropriate weight given for communications. Figure 2 illustrates that, without appropriate assessment tracking, an instructor may inadvertently over- or under-assess specific criteria.

Using this outcomes-based methodology can yield valuable formative feedback provided that the data are reviewed throughout the semester. Figure 3a illustrates the time-sequenced class-average performance against the five ABET criteria for CHE 3120. An assessment of all course requirements was made following each exam. This includes exam scores, homework, projects, etc.—all-inclusive. Exam peri-

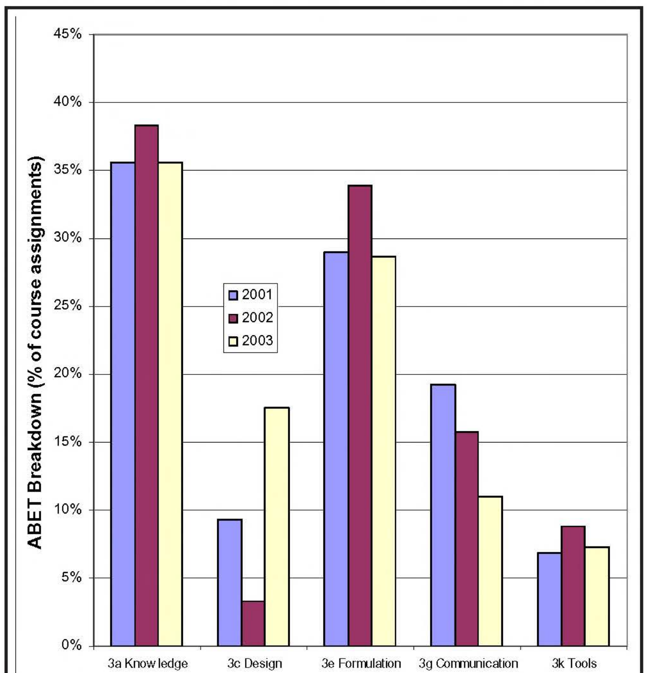

Figure 2. *Term-end ABET breakdown for three consecutive years (2001-2003).*

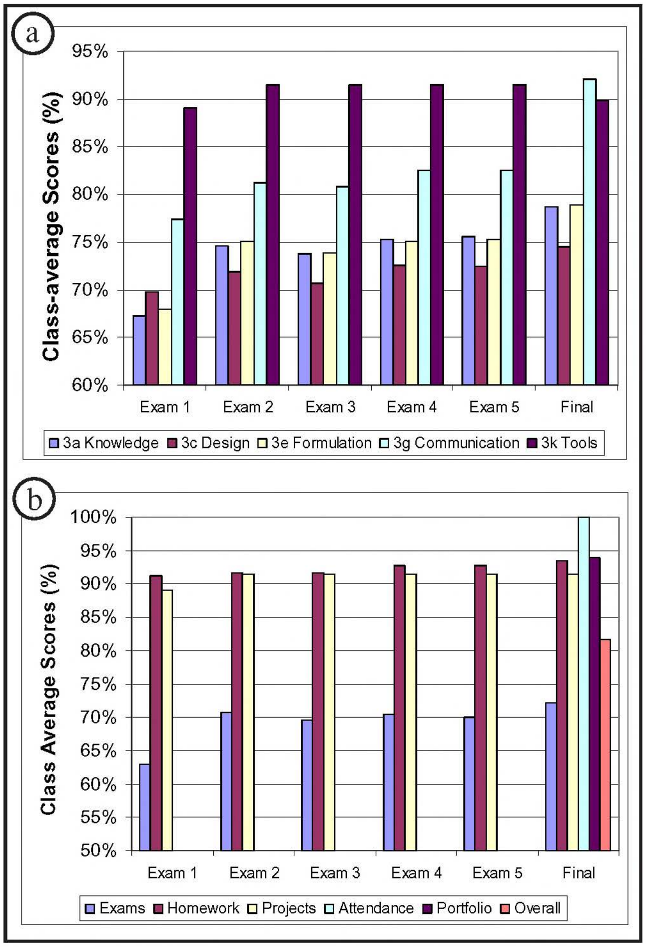

Figure 3. *(a) Time sequence, class-average scores against ABET criteria for 2001.* ***(b)*** *Time sequence, class-average scores against requirements, attendance, and portfolios were assessed at term end as well as the overall score.*

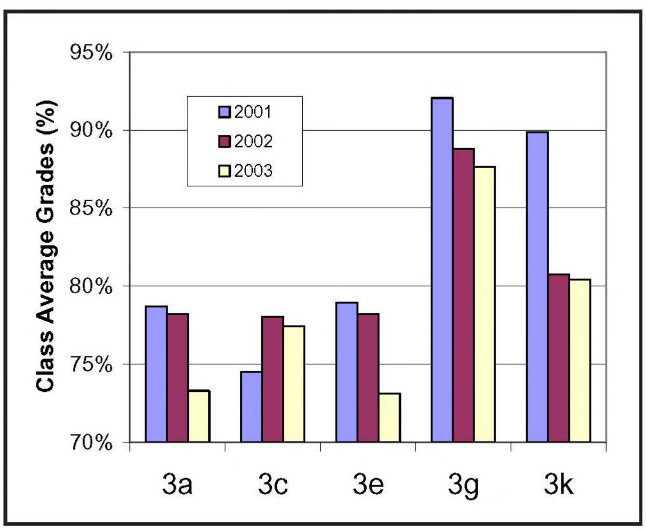

Figure 4. *Class-average term-end performance against ABET Criterion 3a (knowledge), 3c (design), 3e (formulation), 3g (communication), and 3k (tools).*

ods were used rather than uniform chronological periods since coursework can sometimes be somewhat nonuniformly distributed in time. This data can be compared to Figure 3b, time-sequenced performance on a requirements basis.

The requirements-based analysis can tell an instructor how students perform on various forms of assessment, *i.e.,* exams, projects, homework. As expected, students clearly perform better on homework (>90%) and projects (>90%)—forms of assessment that offer students more time to find solutions, work in teams, and *practice engineering* in a more *open* environment (see Figure 3b). At the same time, exam scores, which were typically but not exclusively in-class activities, hardly exceeded 70%. It should also be noted that the attendance and portfolio components of the grade were assessed at term end, although an ongoing approach would likely offer better feedback to both instructor and student. And, while the portfolio has typically been treated as a term-end project containing student-selected course products (*i.e.*, exams, reports, homework, etc.), a model for reviewing at one or more midterm points has also been used. A communication-based rubric was applied to assess the portfolio quality.

While providing feedback on a requirements-basis offers a lumped view of how students are performing, it does not offer outcomes-based insight into *what they are doing well* or more importantly, *what they may not be doing well*. Figure 4, on the other hand, offers a view of student performance against the instructor's goals (outcomes). In this case it was clear that during the first two semesters, 2001 and 2002, students had excellent mastery of engineering tools (Criterion 3k) and a good command of communication skills, with scores upwards of 80%. Knowledge (Criterion 3a) and formulation (Criterion 3e) lagged behind, with design (Criterion 3c) scores being even lower. While none of these scores suggested a problem with this student population, they clearly identified which areas might be focal points for instructional emphasis.

Since design was identified as the most challenging area for students, during the third year of this experiment a conscious effort was made to not only increase design content, but also to emphasize design concepts through lecture, homework, and projects. Figure 2 illustrates the outcomes-based course breakdown for the three-year period of 2000 through 2003, and Figure 4 illustrates term-end class-average performance for the same period. While emphasizing design concepts did not produce an obviously better outcome (*i.e.*, improved scores on the design-related course elements), student scores as compared to the cumulative average of the prior two years were marginally higher but still well within the year-to-year variability. Surely, one would hope that emphasizing a concept would lead to improved student performance, and while the proposed method of formative and summative course-level assessment of outcomes criteria makes it possible to make such course-level changes, a more detailed long-term study is required to validate cause and effect of using this strategy. Such a study should include a control group that does not use the new accounting strategy. At least three years of data in several course formats, *i.e.,* lab, lecture, etc., should be included. Input from an external assessor, such as an ABET reviewer, would also be extremely valuable.

Experience in other learning environments

The outcomes-base strategy was also tested in other learning environments, including a self-learning environment (required seminar), a discovery-based environment (nontraditional technical elective), and a hands-on environment (laboratory). These courses also used a broad range of assessment protocols (tools), including term projects, oral presentations, assessments of team interaction, and similar, more authentic forms of assessment.[16,17] Thereby, the proposed outcomes-based scorecard was tested in an environment of broadly differing outcomes as well as with tools that are widely considered to provide a "richer" form of assessment than exams and homework alone. While the accounting and mapping strategy was the same in each case, the outcomes selected were considerably different and in some cases represent the more difficult to quantify of the ABET criteria—thus providing a test bed for evaluating the practicality and functionality of the methodology for the entire range of ABET outcomes.

The chemical engineering department at TTU offers a seminar course titled "Developing Areas in Chemical Engineering." It was broken into three requirements: attendance, homework (weekly assignments), and a term project. Students were required to submit weekly assignments that were designed to facilitate their ability to engage in the process of self-education (a lifelong learning skill). The first assignment was to define lifelong learning. Other assignments included writing a column about microelectromechanical systems (MEMS) for a popular science magazine, researching a micromachining technology, reviewing a technical publication, and inventing a micromachine concept. The course culminated in short presentations and a brief written paper describing the micromachine each student invented.

The outcomes selected for the course included ABET criterion 3e (formulation), 3g (communications), and 3i (lifelong learning). The lifelong-learning goal was typically addressed in terms of how well the student was able to find the resources needed to answer a question, and the form of articulation used apart from simply the ability to communicate well.

"Interdisciplinary Studies in Ceramic Materials Engineering," a course co-offered, developed, and taught by Mechanical and Chemical Engineering,[18] was also part of the study. In this case, ABET Criterion 3d (ability to function on multidisciplinary teams) was included; again, a rather difficult criterion to assess. The interdisciplinary and teaming aspects are addressed in this course by offering students rather open-ended research problems that require a multidisciplinary approach. Teams and individuals conduct self-assessment and peer assessment, and the scores are kept in the manner defined by the ABET course-level accounting strategy defined above. Finally, a hands-on laboratory course was also included in this experiment. ABET Criterion 3b, as well as team aspects of 3d (not necessary multidisciplinary), were the focal outcomes. While authentic assessment activities, rubrics, and metrics for lifelong learning and team interaction will be debated at length for some time, the course-level strategy presented here was found to provide a basis for quantifying obvious elements of these processes.

After three years of pilot testing this methodology in a broad range of courses that included a traditional lecture-based course, a discovery-based research-oriented environment,[18] and a self-directed seminar, several course-level improvements have been made as the result of the outcomes-based assessment data. These can be generalized into two categories: (1) altering course content to change the outcomes-based breakdown, and (2) modification of course content to emphasize outcomes with low performance scores. In the lecture-based stage-wise separations course, the course breakdown was altered to increase design content and decrease communications content. Content emphasizing design—including in-class workshops, more use of computer simulations, and lectures on design methodology—was included. In the more open-ended courses, "Interdisciplinary Materials Engineering," "Chemical Engineering Lab II," and "Developing Areas in Chemical Engineering," systemic problems were identified in the area of written communications and research methodology. Performance scores on communication (Criteria 3g) and experimentation (Criteria 3b) were low. Surprisingly, some students could not organize their thoughts to produce a good research report, conduct literature review, or design an experiment (thinking through the steps associated with identification and specification of an experiment). Similarly, their information-interpretation skills were weak, which translated into low-quality research reports. Outcomes-based scorekeeping helps to identify and quantify such deficiencies and to track the response to changes in the classroom. Course content was altered in each case to include in-class workshops and mini lectures on skills-based topics that would otherwise not be included in such classes, *i.e.,* research-report writing, the scientific method, and discovery-based learning.

Suggestions for using the course-level strategy in the overall context of program-level continuous improvement

The course-level outcomes-based assessment strategy presented here has a number of advantages, including real-time loop closure at the instructional level. It also has a number of disadvantages, including a significant one-time start-up effort and some additional effort to prepare and grade assignments in a nonconventional way. Once implemented, however, this strategy could provide a new way of optimizing instructional efficiency. Furthermore, while this experiment focused on applying the outcomes assessment to the course-level, the approach may have significant utility if applied, even on a limited basis, throughout the curriculum, to quantitatively address issues of feedback both at the curriculum level and the course level. For example, if students are found to be particularly weak in ABET Criterion 3a (ability to apply knowledge of . . . mathematics . . .), the source of the deficiency may be in the prerequisite course sequence. If applied to a significant number of courses within the department, trends that suggest such deficiencies would be quantitatively identifiable. This form of quantitative information would then become one of a number of indicators that could be used to improve student performance through curriculum-level continuous improvement.

Ultimately, the objective should be to integrate course-level information into an integrative process that is summative and probes *deep* retained learning rather than superfluous short-term learning. If strategically implemented throughout the curriculum to include early, mid-curriculum, and capstone courses, this methodology may have value as one part of a comprehensive evaluation system.

Yet another benefit of using an outcomes-based performance accounting strategy is possibly one of administrative record keeping. Course-end reports including Tables 4 and 5 can be kept. When combined with student portfolios or select student papers, they provide the basis for an ABET exhibit that quantitatively illustrates student performance against ABET criteria as well as a methodology for continuous course and curriculum feedback and improvement.

IMPRESSIONS AND RECOMMENDATIONS

Since the ABET criteria address a broad range of skills, an ABET-based course-level approach for using assessment outcomes was implemented and assessed in laboratory-, lecture-, and seminar-based settings. The use of a systematic mapping between the requirements domain and ABET domain provides a detailed record of student performance against ABET Criterion 3 Outcomes (Tables 3, 4, and Figure 4). The strategy described here is time consuming at first, but once established, it is no more labor intensive than other methods and yields far more insights into the teaching and learning processes. While the traditional approach neatly itemizes the overall performance on individual course requirements (something that every instructor and student wants to know), it gives no insight as to what are the strengths or weaknesses based on any performance criterion (Figure 3b). The ABET scorecard, however, itemizes the overall performance by the specific performance criteria and offers the instructor a window into student skill-based abilities (Table 4). Both are important and both should be considered when assessing student performance and when addressing course improvement.

Streamlining the process on the front end and providing faculty training and retraining in this new ABET-based course-level strategy should make it a more attractive alternative for faculty to implement. A more extensive experiment is needed to validate and extend the results presented in this case study. Additional test beds wherein other departmental and extra-departmental faculty adopt the strategy must be included in the next level of the experiment. Direct feedback from an ABET review team should be sought during the next review cycle in 2009. Furthermore, elements of skill level should be included in the assessment matrix using, for example, *Bloom's Taxonomy*, or a similar model.

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WEB-BASED DELIVERY OF ChE DESIGN PROJECTS

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Leading chemical engineering faculty, in a series of three workshops titled "New Frontiers in Chemical Engineering Education," have identified a need for case studies to support the unifying curricular themes of molecular transformation, multiscale analysis, and systems approaches.[1] As a result of this workshop series, case studies are sought that provide real-world context, including aspects of safety, economics, ethics, regulations, intellectual property, and market/societal needs. In addition, the desired case studies should provide real-world challenges—open-ended, complex problems with incomplete data that require pruning of alternatives.

Note that the term "case study" has many meanings. There is a large body of literature on using "cases" for the purpose of student instruction, primarily in the disciplines of business and law but more recently in the engineering literature.[2-4] In this context, the "cases" are brief (one- to two-page) descriptions of an actual problem where students are challenged to analyze the situation and formulate a response, taking into consideration all of the facets of the open-ended problem.

Another type of case study is really a short (one- to five-page) problem statement that identifies the product or process, the design basis, associated process constraints or specifications, assumptions, and required deliverables. Several recent chemical engineering design textbooks[5-7] contain text or accompanying CD versions of design problem statements. CACHE, a not-for-profit educational corporation, makes available selected design case studies with solutions.[8] Our concept of a case study involves not only the problem statement, but associated technical briefs and solution information that provide an introduction to the material, both for the students and for the mentoring faculty.

The formulation of design projects presents three major challenges: the project expectations must be challenging yet attainable, the scope must encompass the essence of industrial practice and represent a realistic situation, and—possibly most challenging to the instructor—the technical focus of the topic must be such that the project advisor (usually the faculty member responsible for the course) is able to provide adequate guidance, support material, and mentorship to the students.

For this project the first objective was met by using design projects completed by previous years' design groups. The final reports were then compiled and the best sections or portions of the solutions condensed into a single exemplary solution. Following a review of the "solution," sections deemed incomplete were made part of the deliverables assigned to the subsequent year's project team. This is not to imply that the solution presented is the only reasonable solution available—as with all engineering projects, many solutions can be considered viable and the students are encouraged to think creatively when determining a solution.

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The second objective was realized through the involvement of industry professionals in the formulation of the design problem and the mentoring of the teams responsible for the project report. These practitioners also reviewed the solution material and provided additional suggestions for completion of the case study materials. For example, because of the novelty of the biotechnology-related projects, much of the initial solution material generated by student groups focused on material that was new to chemical engineering practice, *i.e.*, validation protocols for equipment, inoculation and cell cultivation, and biomass processing. The solutions lacked basic engineering data for equipment sizing and utility usage, and thus were vague as to how production costs were actually calculated. This year's students will be addressing these issues and their results will be added to the support material for each exemplary solution.

Design projects present three major challenges: The project expectations must be challenging yet attainable, the scope must encompass the essence of industrial practice and represent a realistic situation, and . . . the technical focus of the topic must be such that the project advisor . . . is able to provide adequate guidance, support material, and mentorship to the students.

The case study represents our effort to address the third challenge. Some chemical engineering faculty members may want support for the biotechnology projects if they lack practical experience in this field. At North Carolina State University (NCSU) we are fortunate to have faculty with biochemical engineering expertise as well as industrial mentors through the local ISPE (International Society of Pharmaceutical Engineering) chapter, with NCSU students also having access to internships with local pharmaceutical companies and manufacturers. The industrial mentors supplied by ISPE were especially helpful in developing the information for the two biotechnology case studies.

TABLE 1
Typical Senior Design Course Projects

- AlphaVax: A Facility Retrofit for Vaccine Production
- SuperPro®-Based Ammonia Plant Retrofit
- Biodiesel Facility Utilizing Waste Vegetable Oil
- Bio-Methanol and Bio-Ethanol Facility: A Feasibility Study
- Ceramic Processing
- Citric Acid Production Facility Case Study
- Production of an Antigenic Co-Protein Line for PeptiVax Pharmaceuticals
- Innovative Design of a Snowboard
- Carbon Dioxide Separation: High Temperature Flue Gas Adsorption
- Reducing the Risk of Cancer from Fried Foods
- 1.2 kW Portable Fuel Cell System
- Combined Heat and Power Fuel Cell System for NCSU
- Gasification of Biomass: Conversion to Higher Value Chemicals and Fuels
- Designing a Gelatin Manufacturing Plant for North Carolina
- Kennametal Waste Minimization
- Medical Waste Treatment Process: for Use in Underdeveloped Areas
- Microfluidic Cooling Device for Microprocessors
- Perchlorate Treatment for Domestic Water Systems
- The Biological Production of para-Hydroxybenzoate
- Thermochemical Processing of Tobacco to Produce Methanol: A North Carolina Facility
- RESS Production of Micronized THC Particles in Solution, for Pulmonary Delivery
- SuperPro® Modeling and Optimization of Conjugate Vaccine Facility

COURSE STRUCTURE AND LOGISTICS

At NCSU, the capstone design class consists of a two-semester design sequence. The complete course Web site for CHE 451 (spring 2004) is included in the "Helpful Resources for Instructors" on the case study Web site. The first semester is primarily focused on instruction, including economic analysis, process simulation, environmental impact, and life-cycle analysis, etc. In previous years the students did not start their capstone project until the second semester; the instructors have found, however, that it is more effective to launch the project early—mid-semester in the fall—and continue it through the spring. This allows much more time for the students to do an in-depth literature and patent search early in the life of the project, as well as to invest considerably more time in the project as a whole. The instructors establish expectations that each student in the project group will invest at least 10 hours per week throughout the project life. The solutions that are available to instructors reflect the effort of one and a half semesters (approximately 6 months), but instructors can "prune" the list of deliverables as appropriate to match the time available.

Typically a capstone class at NCSU has an enrollment of 85 to 95 students. In previous years there were four to five projects (typically traditional simulation-based projects) and four to five teams working on each project in parallel, but in recent years the instructors have tried to come up with as many as 20 to 22 unique projects so that each team has its own project. Typical project titles for the design course are shown in Table 1.

The case studies described in this paper had one team of four to five students working on the case. Again, depending on the class size and duration, it would be feasible to have more than one team working on the problem, each being assigned to different aspects of the design.

As part of the course deliverables, student teams developed team expectations and established a project management system to report time on a weekly basis. Peer evaluations, completed at mid-semester and at the end of the semester, were used to weight individual grades based on group work. The instructors met weekly with teams and/or project managers to monitor progress. Templates for grading written and oral reports, peer evaluation forms, and examples of group time logs are included on the Web site under "Helpful Resources for Instructors."

At the end of the semester, the Chemical Engineering Department sponsored a "Senior Design Day." One student from each group made a brief (2-minute) overview presentation using PowerPoint, and then the group adjourned to a poster session. Each group prepared a poster and responded to questions from those attending the session. Chemical engineering faculty, industrial sponsors, multidisciplinary faculty, and parents were invited to Design Day.

CASE STUDY STRUCTURE

To simplify accessibility of the case studies, the information contained on the Web sites, and the Web sites themselves, are structurally similar. The case study information can be broken up into three major components: the problem statement, support information, and exemplary solution.

The *problem statement* contains the basic information that the student needs to get started on the project. The general purpose of the project, raw-material specifications, basic operating parameters and systems, reaction kinetics, and product specifications are included in this section. *Support information* includes a list of starting references, technical briefs on relevant processes (created by previous years' project teams), facility layouts, equipment lists, and suggested deliverables for the project teams. The *exemplary solution* provides a complete project report, including an executive summary, introduction, technical background, process description, waste management plan, regulatory review, facility design, validation/commissioning plan, detailed manufacturing costs, detailed spreadsheet calculations for material balances, equipment sizing, utility usage, profitability analysis, and process simulation results.

CASE STUDY ACCESS AND EXAMPLE

The Web site contains three complete case studies for the production of vaccine co-protein, ammonia, and citric acid. The structure of the Web site, and exemplary material based on the co-protein project, illustrate the nature and detail of the case studies. The reader should keep in mind that this is not "Web-based instruction," but rather a source of instructional material which can be accessed via the Web. While this material may be adapted to a Web-based instructional scenario, that would be the responsibility of the faculty implementing the material.

Students and faculty can access all of the case studies shown in Figure 1 from the main page of the Web site at

<http://www.ncsu.edu/checs/>

The Web site is divided into two levels of access: student and faculty. As shown in Figure 2, students have access to descriptive information about the project, information on each case study, and resources related to the case studies (Web-based, books, journal articles, PowerPoint tutorials, etc.) Faculty can access the same information as the students, but in

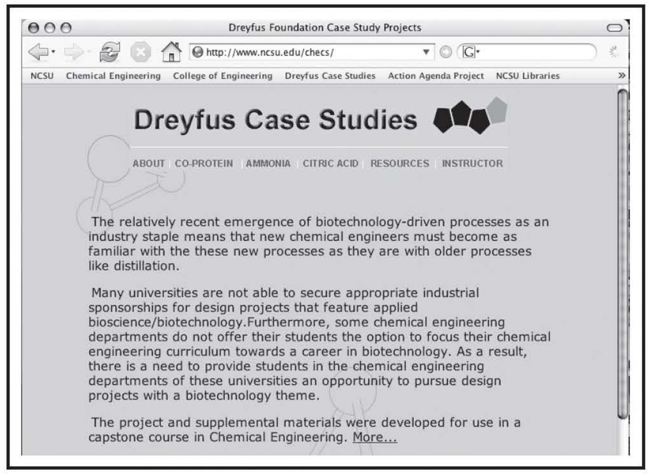

Figure 1. *Home page for case study Web site.*

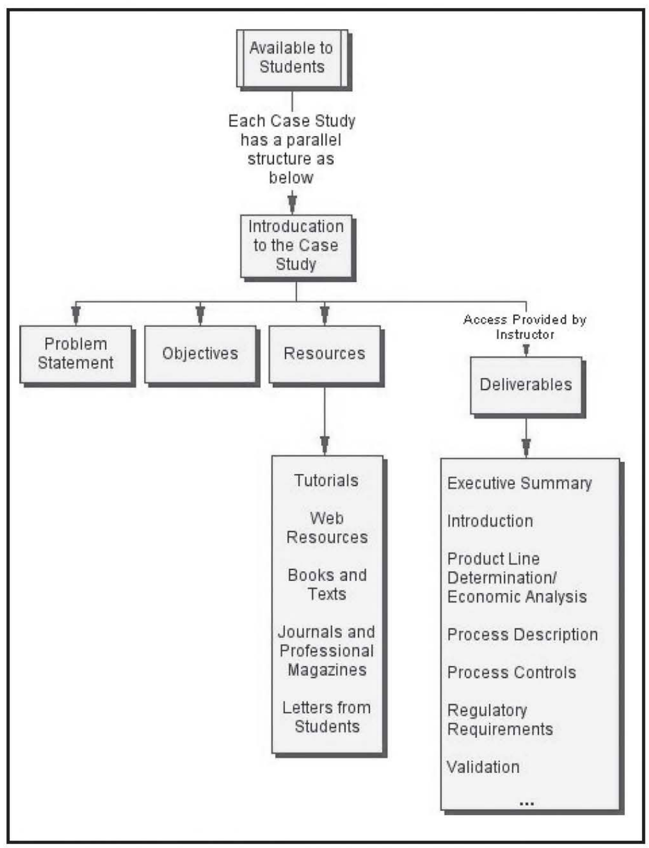

Figure 2. *Web site structure: Student view.*

addition, the exemplary solution and additional resources are available to them through a password-protected protocol. Examples of materials that are available to the instructor are shown in Figure 3. The instructor requests password access through an online registration page marked "Instructor" on the main page. The instructor's request is forwarded to the authors, who will verify the instructor's status and provide a user ID and a password. The authors will solicit feedback from faculty who use these cases regarding questions, problems, or suggestions for additional material to be included. This feedback will be used to improve the case study materials.

CASE STUDY INFORMATION: CO-PROTEIN

To indicate the organization and the ease of comprehension of the Web site, examples of the problem statement, a list of deliverables, student letters, and tutorials are described below.

Problem Statement and Deliverables

The problem statement is detailed since most chemical engineering students have little experience with biological systems, and the proteins and processes described are "disguised" so as to avoid disclosure of proprietary information on the part of the original project sponsor.

PeptiVax Inc., a biotechnology company, has developed several co-proteins that may help in the fight against several common viral diseases. In test animals, each co-protein attaches to a target virus and the virus-protein complex stimulates the production of antibodies against the virus. This cooperative system may also enable the human body to produce a small amount of antibodies that will limit the spread of the virus. Several of these antigenic "co-proteins"—co-Hep B, co-Hep C, co-Human Papilloma Virus, co-RSV, co-Rotavirus, and co-HIV—are now in Phase I clinical trials (see Table 1 *[contained on the Web site]* **for protein characteristics). The management of PeptiVax Inc. would like your group to evaluate and recommend a proposed product line, design the corresponding *Escherichia coli*-based processes for protein production (see Table 2** *[contained on the Web site]* **for *E. coli* growth data), and determine the required modifications to their existing facility (see Figure 1** *[contained on the Web site]* **and Tables 3 and 4** *[contained on the Web site]***).**

PeptiVax's senior management would like to see the following information and deliverables:

- **United States Target Market and Market Size**
- **Intermediate and Final Product Descriptions**
- **Major Regulatory Requirements of the U.S. market**
- **Project ROI and Product Cost**
- **Process Summaries**
- **Descriptions of all Facility Modifications**
- **Capacity and Annual Schedule, Based on Market Potential**
- **Preliminary Design/Construction/Validation/Regulatory Schedules**

PeptiVax's technical and regulatory personnel would like to see the following:

- **Process Flow Diagrams (PFDs)**
- **Process Description**
- **Material Balances (Raw Materials, Product, Waste, etc.)**
- **Equipment Lists, with Specifications**
- **Control System Requirements (new systems)**
- **Facility Floor Plan, Indicating Material/Personnel Flows**
- **Utility Requirements**

Product line proposals should be accompanied by an economic analysis of the potential market value of each co-protein. This should include a detailed description of the corresponding viral infections combated by each co-protein, and the current United States infection rates. The design process for any proposed product line should be based on the assumption that all the co-proteins are produced extracellularly by a specialized strain of the recombinant host organism, *Escherichia coli*. Each recombinant strain of *E. coli* will be able to produce one and only one of the potential co-proteins. The individual co-protein characteristics are presented in Table 1 *[contained on the Web site]*. **Keep in mind**

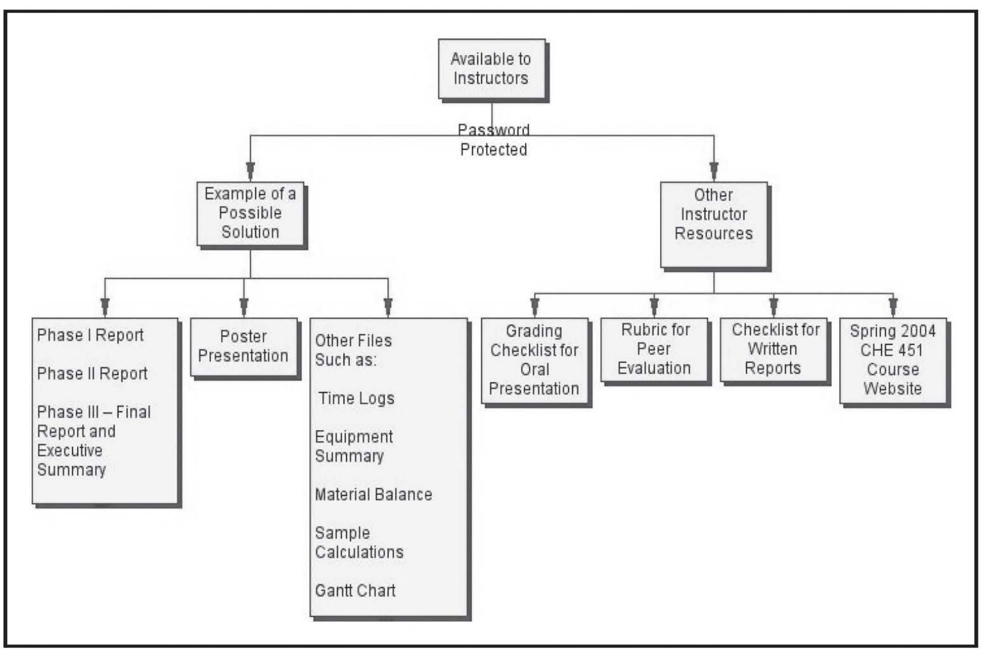

Figure 3. *Web site structure: instructor view.*

that the required modifications to the existing PeptiVax facilities should take into account the amount of each co-protein needed to capture the desired market share over the course of one calendar year.

This information is sufficient for the design team to understand the needs of the project sponsor.

This section is followed by the table of contents for the project deliverables, shown below.

1. *Executive Summary*
2. *Introduction*
3. *Product Line Determination/Economic Analysis*
4. *Process Description*
5. *Process Controls*
6. *Regulatory Requirements*
7. *Validation*
8. *Waste Management*
9. *Facility Design*
10. *Detailed Costs of Proposed Product Lines*
11. *Conclusions*

Each item in the table of contents is a link to a page in the Web site that contains a brief (one- to two-paragraph) definition/explanation of that item. For example, the Process Description link will take you to a page with the following information:

> *What is expected: The economic analysis performed above gives upper management at PeptiVax enough information to determine what drugs should be produced. This is based on the anticipated market capture and on approximating the cost of producing a recombinant drug. The numbers generated are rough estimates, however. In order to calculate a detailed manufacturing cost and to design the facility to accommodate the equipment necessary for the production of these co-proteins, the specific manufacturing process for each co-protein is required. Before a specific process can be developed, it is necessary to understand the different equipment that can be used in a biotechnology process. This information can then be used to streamline the process by using the minimum number of unit operations required for each co-protein production. To be included in this deliverable are:*
>
> - *Overall description of protein production process*
> - *Complete process block flow diagram*
> - *Unit operation descriptions of each process unit*
> - *Material and energy balance*
>
> *Need more help on Fermentation and Purification overviews? See the Fermentation and Purification tutorials in the Resources section.*

The explanations are sufficiently general to allow further refinement by the individual instructor but sufficiently detailed to allow the team to begin work on the item in question. There are also links to relevant tutorials through the Resources link (note: the Resources link is on the home page).

Letters from Students

This section contains letters from former design teams with advice regarding project management, preparing oral and written presentations, and general words of encouragement. A brief example regarding oral and written presentations is shown below.

Recommendations and Lessons Learned from Co-Protein Group (taken directly from student comments):

Written Report

1. Create outline for proposal and phase reports before actually writing.
2. Don't underestimate the importance of writing versus technical content.
3. Get connected with technical advisors and use to full advantage.
4. Schedule regular meetings with advisor.
5. Schedule regular weekly or biweekly meetings with group.
6. Get an outside English teacher or technical-writing advisor to review all reports.
7. Set goal to complete technical aspects of report the week before due date, so that the last week may focus on writing quality (i.e. grammar, sentence structure, etc.)
8. In group meetings, whether before or after each phase has been completed, discuss each person's section. Each person should have a thorough understanding of everything in the report, including all assumptions made and all calculations.
9. Use reader's comments from each phase, to build on them for the next phase.
10. Choose a project that you have sincere interest in. This will help keep you motivated and interested throughout the semester.
11. Don't get discouraged—everything comes together.
12. There is no "real" structure and requirement for what is to be included in the final project—it really depends on how you got there.
13. Do not look for specific outline of what needs to be done when starting project—start on your own and think of what seems reasonable to accomplish.

Oral Presentation

1. Transition between every slide.
2. Go over "pretend" responses to question-and-answer period—be prepared for questions (or how to respond to questions) you do not know.
3. Request to go first.
4. Don't use white background—always use blue or a dark color.
5. Make sure that all figures and tables are legible. If this is not possible, make handouts for everyone to see.

6. All group members presenting should stand.
7. Practice, practice, practice.
8. Assign a person responsible for every section of the presentation so that they can field questions. This will prevent confusion and looks of helplessness during the question-and-answer session.

While much of this advice is identical to that which the professor would give, there is added validity when it comes from the mouth (or pen) of a peer!

Tutorials and other Resources

The Resources link from the main page takes the students to a list of references (Web sites, tutorials, books, and professional journals) that will help them get started on uncovering the technical background for their project. The resource page for the co-protein project is summarized below.

Co-Protein Case Study Resources
Web resources/tutorials/texts and books/journals/professional magazines
Web Resources (these are links to other parts of this page)

CDC Hepatitis Information Page
<http://www.cdc.gov/ncidod/diseases/hepatitis/index.htm>
MedicineNet.com <http://www.medicinenet.com>
HIVandHepatitis.com <http://www.hivandhepatitis.com/#hepc/tmhepc.html>

CDC Rotavirus Information Page
<http://www.cdc.gov/ncidod/dvrd/revb/gastro/rotavirus.htm>

CDC Human Papillomavirus (HPV) Information Page
<http://www.cdc.gov/nchstp/dstd/HPVInfo.htm>

The Respiratory Syncytial Virus Info Center
<http://www.rsvinfo.com>

American Lung Association RSV information
<http://www.lungusa.org/diseases/rsvfac.html>

CDC HIV/AIDS Information Page
http://www.cdc.gov/hiv/dhap.htm

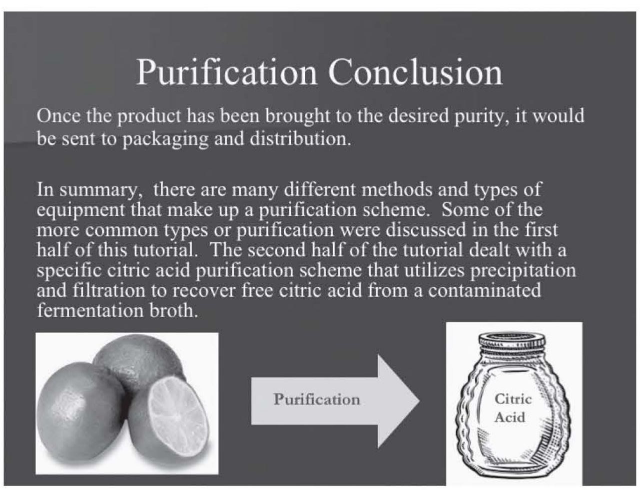

***Figure 4.** Example from purification tutorial.*

Technical Briefs:
Overview of Fermentation (ppt) (pdf)
Overview of Purification (ppt) (pdf) (see Figure 4)
Validation Tutorial (ppt) (pdf)
Overview of Facility Design (ppt) (pdf)

Books and Texts:
Bailey, J.E., and D.F. Ollis, *Biochemical Engineering Fundamentals*, 2nd ed., McGraw-Hill Book Co., New York, NY 1986
Shuler, M.L., and F. Kargi., *Bioprocess Engineering Basic Concepts*, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 2002

Journals/Professional Magazines:
Pharmaceutical Manufacturing, PutmanMedia <www.pharmamanufacturing.com>
Chemical Processing, PutmanMedia <www.chemicalprocessing.com>
CONTROL for the process industries, PutmanMedia <www.controlmag.com>

Note that the tutorials are available in both PowerPoint and pdf formats (**ppt** denotes a PowerPoint file: will open in Internet Explorer or Microsoft PowerPoint; **pdf** denotes an Adobe pdf file: requires Acrobat reader.)

SUMMARY

Three case studies have been developed for use by the chemical engineering community. Two of the three case studies are in the area of bioprocessing, which allows faculty who may not have extensive background in this area to provide students with relevant materials. The authors would like to encourage readers to use these case study materials and provide feedback on enhancements, gaps, or other opportunities for improvement.

ACKNOWLEDGMENTS

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SCREENS DOWN, EVERYONE!
EFFECTIVE USES OF PORTABLE COMPUTERS IN LECTURE CLASSES

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Portable computers are getting more powerful and cheaper all the time. Most college students now own one, and many engineering and science curricula require all their students to have them. Once colleges do that, though, they are also obliged to give the students enough to do with the computers to justify that requirement. True, homework involving computers is routinely assigned in technical curricula, but the computer labs at most colleges are more than adequate to serve the students who don't have their own computers. Few institutions have enough computer-equipped classrooms to host all their classes, however, and so it makes sense to have the students use their own computers in class. The question is, to do what?

Taking notes in class is not the answer. Lecture notes in engineering, science, and math courses normally involve equations and diagrams, which students cannot enter on a computer nearly as fast as instructors can write them on a board or project them on a screen. Unless the students are given better options, they are more likely to use their computers during lectures to work on homework, play games, surf the Web, and e-chat with their friends. It's hard enough for instructors to hold students' attention in a lecture class under normal circumstances; adding computers with all of the tempting diversions they offer can make it hopeless.

The remedy for attention drift in class—with or without computers—is to use *active learning*,[1] periodically giving the students things to do (answer questions, solve problems, brainstorm lists, . . .) related to the course content. Extensive research has established that students learn much more through practice and feedback than by watching and listening to someone telling them what they are supposed to know.[2]

Computers can be effectively incorporated into classroom activities in many ways for a variety of purposes. Several examples follow.

Working through interactive tutorials

Computer-based tutorials can be highly instructive, especially if they are interactive, prompting users for responses to questions and correcting mistakes. Tutorials are increasingly common on CDs bundled with course texts, and they may also be obtained from software companies and multimedia libraries such as MERLOT or SMETE.[3] A problem is that students worry about how much time they will take and so tend to ignore them. An effective way to deal with their concern is to have them work through the first of a set of tutorials. If it is well designed, they will then be much more likely to work through the others voluntarily. (A recent research study illustrates this phenomenon.[4])

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Rebecca Brent *is an education consultant specializing in faculty development for effective university teaching, classroom and computer-based simulations in teacher education, and K-12 staff development in language arts and classroom management. She codirects the ASEE National Effective Teaching Institute and has published articles on a variety of topics including writing in undergraduate courses, cooperative learning, public school reform, and effective university teaching.*

Getting started with new software and building skill in its use

Many students—even those comfortable with e-mail and computer games—feel intimidated when unfamiliar software is introduced in a course. To help them over this psychological barrier, have them run the software in class, working through the same kinds of tasks they will be called on to carry out in assignments. When they get confused or make common beginners' mistakes, they will get immediate assistance instead of having to struggle for hours by themselves and will then be prepared to run the software on their own. Several in-class activities may subsequently be used to help them gain expertise in the software, such as:

- *What will happen?* Give one or more statements or commands and ask students to predict what the program will do in response. Then have them enter and execute the commands and verify their predictions or explain why they were wrong.
- *What's wrong?* Give statements or program fragments with errors and ask the students to identify and correct the mistakes.
- *How might you do this?* State desired outcomes and ask the students to write and test programs to achieve them.

Carry out Web-based research

Answers to many research questions can be obtained in a few keystrokes using powerful search engines such as Google. To help your students develop computer research skills, you might ask them to do several things in class and then in homework assignments:

- Gather information about a specified device, product, or process.
- Locate a visual image to illustrate a concept or include in a report.
- Verify or refute an assertion in the popular press related to science or technology.
- Assemble supporting arguments for different sides of a controversial current issue.

Explore system behavior with simulations

Computer simulations allow students to explore system behavior at conditions that might not be feasible for hands-on study, including hazardous conditions. Having students build their own simulations of complex systems in class may be impractical, but prewritten simulations (which might include random measurement errors and possibly systematic errors) can be used for a number of worthwhile activities:

- *Study simulated experimental systems in lecture classes.* Ask students to (a) apply what they have learned in class to predict responses of a simulated system to changes in input variables and system parameters, (b) explore those changes, interpret the results, and hypothesize reasons for deviations from their predictions, and possibly, (c) explore or optimize system performance over a broad range of conditions.
- *Prepare for and follow up real laboratory experiments.* Have students in a laboratory course design an experiment and test their design using a simulation before actually running the experiment. Following the run, have them formulate possible explanations for discrepancies between predicted and experimental results.

Implementation tips

Several formats for computer-based activities in class should be used on a rotating basis. If all students have computers, they may work individually, or in pairs or trios, or individually first and then in pairs to compare and reconcile solutions. If there are only enough computers for every other student, the students may work in pairs with one giving instructions and the other doing the typing, reversing roles in successive tasks. After stopping an activity in any of these formats, the instructor should first call on several individuals for responses and then invite volunteers to give additional responses. The knowledge that anyone in the class might be called on will motivate most of the students to actually attempt the assigned tasks.[1]

Finally, an indispensable device for effectively using portable computers in class is the simple command, "Screens down!" when you want the students' attention for any length of time. As long as they can see their screens and you can't, the temptation for them to watch the screens instead of you can be overwhelming. If you take away that option, at least you'll have a fighting chance.

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

COMMON PLUMBING AND CONTROL ERRORS IN PLANTWIDE FLOWSHEETS

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Almost all senior design courses discuss only the steady-state economic aspects of process design and exclude any consideration of dynamic behavior. Very few design textbooks even mention dynamics and control.[1,2] Given this tendency, the senior design course at Lehigh University is apparently quite distinctive in that it emphasizes "simultaneous design," *i.e.,* the consideration of both steady-state economics *and* dynamic controllability at the early stages of conceptual design. A detailed discussion of the need for and the importance of this simultaneous approach has been presented in a recent book.[3]

The Lehigh design course requires two semesters. In the fall, traditional steady-state synthesis covers steady-state computer flowsheet simulation, engineering economics, equipment sizing, reactor selection, energy systems, distillation separation sequences, azeotropic distillation, and heuristic optimization. In the spring, dynamic plantwide control covers dynamic computer simulation, pressure-driven plumbing, control structure development, and controller tuning.

Commercial flowsheet simulation software is now sufficiently user friendly that undergraduates can produce steady-state and dynamic simulations of fairly complex processes. Computer speed has increased to the point that dynamic simulations of fairly complex flowsheets can be run in reasonable times. Figure 1 presents an example of a flowsheet generated by a senior design group. Note that all the plumbing details are not given in the flowsheet, particularly the overhead piping, valves, reflux drum, and pump.

The organization of the Lehigh course has three-person groups, with each group working on a different design project. These projects are supplied by an industrial consultant who works with the group throughout the year. Active and retired engineers from industry graciously volunteer their time and years of practical experience to this effort. Engineers have participated from Air Products, DuPont, Exxon-Mobil, FMC, Praxair, Rohm&Haas, and Sun Oil.

As educational aids in the area of plantwide control and in the use of commercial dynamic simulators, two textbooks have been written.[4,5] Two basic types of errors are made by many students: inoperable plumbing arrangements and unworkable control structures. We consider these in the following sections.

COMMON PLUMBING ERRORS

The lack of physical understanding of practical fluid mechanics by many students is somewhat alarming. They have learned momentum balances, boundary-layer theory, the Navier-Stokes Equation, etc., in their fluid mechanics course. But when it comes to putting together a piping system to get material to flow around in a process, many students have great difficulty in coming up with a reasonable plumbing system.

The commercial process simulators have contributed to this weakness by permitting *flow-driven* dynamic simulations in which material "magically" flows from one unit to another despite the fact that the first unit is at a lower pressure than the second.

Fortunately *pressure-driven* dynamic simulations are also available. These are much closer representations of reality. Pumps, valves, and compressors must be inserted in the flowsheet in the required locations so that the principle "water flows downhill" is satisfied.

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In my experience about 50% of the problems in designing and operating a real chemical plant involve hydraulics. Students need to have a solid understanding of practical fluid mechanics. Pressure-driven dynamic simulations provide a useful platform for developing this vital plumbing know-how.

The following is a brief compilation of some of the most common plumbing errors that students make in developing flowsheets. It might be useful to also state that I have seen many of these same errors made by presumably experienced engineers on real plants. So perhaps they are not quite as obvious as one might think.

No Valve Installed

Perhaps the most serious plumbing error, and one that is alarmingly common in student flowsheets, is to not have any valve in a line connecting process units that are operating at different pressures. This is illustrated in Figure 2 where a process stream flows from a vessel operating at a pressure of 10 bar into a vessel operating at 2 bar. There must be a valve in this line to take the pressure drop and regulate the flow. The valve can be set by an upstream controller (*e.g.*, level or pressure controllers), or it can be set by a downstream controller. But a valve is required.

Students often state that the pressure can be reduced by just cooling the stream. They confuse a "closed" system having a fixed amount of material with the "open" flow system encountered in a continuous-process flowsheet.

Stream Flowing "Uphill"

Equally distressing is to see a flowsheet in which a process stream is shown as flowing from a low-pressure location into a unit at higher pressure. Students often forget to put in the necessary pumps or compressors.

Two Valves in Liquid-Filled Line

This is probably the most frequently made error. Since a liquid is essentially incompressible, its flowrate is the same at any point in a liquid-filled line. Therefore the flowrate can be manipulated at only one location.

This means there should be only one valve in the line that is regulating the flowrate of liquid. It is physically possible to install two valves in series in a line, but these two valves cannot function independently.

Figure 3 shows several examples of this type of "forbidden" plumbing arrangement. When a stream is split into two streams at a tee in the line, the flow through each branch can be independently set by two valves. The same is true when two streams are combined.

Note that we are talking about *liquid*-filled lines. For gas systems, valves can be used in a line at several locations.

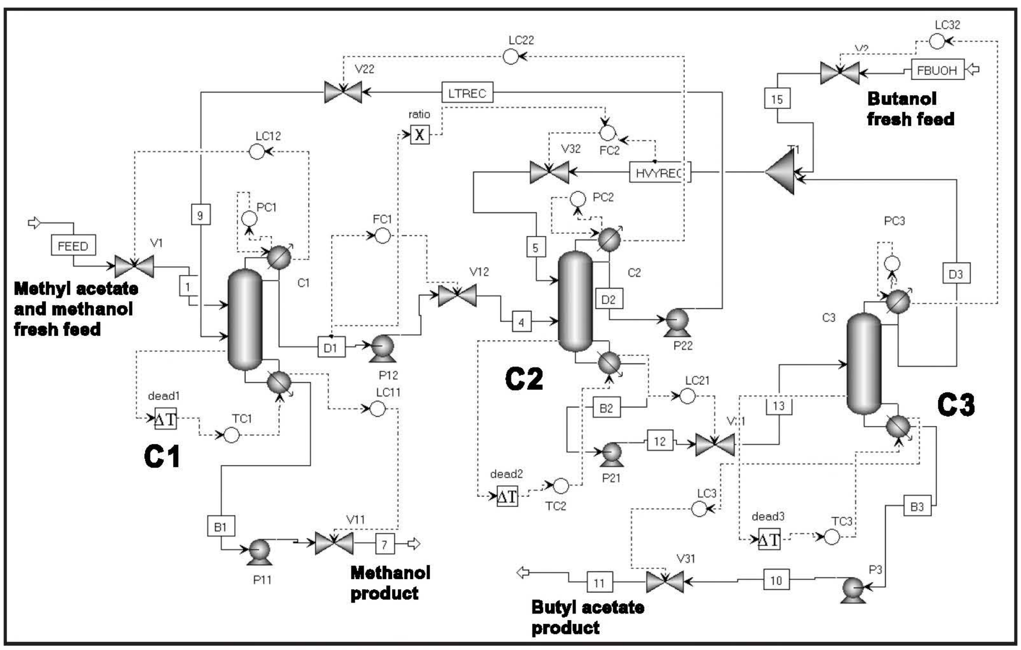

Figure 1. *Example of plantwide control structure.*

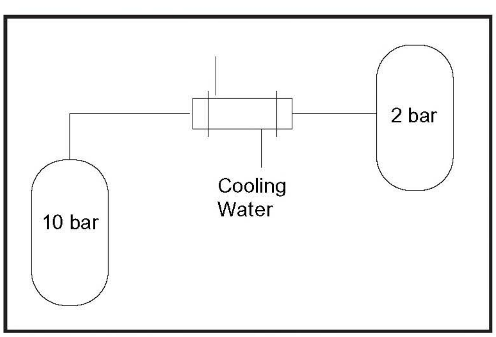

Figure 2. *Missing valve.*

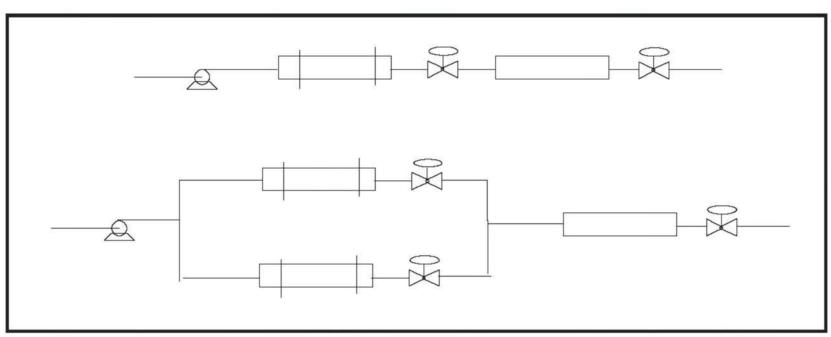

Figure 3. *Forbidden plumbing: two valves in liquid-filled line.*

Figure 4 illustrates this situation. The pressure in the first vessel is regulated by valve V1. The pressure in the second vessel is regulated by valve V2. This is workable because gas is compressible, so the instantaneous flowrates through the two valves do not have to be equal as is the case with liquids. The gas pressure in the process units can vary between the two valves.

Valve in Suction of Pump

Pumps are used to raise the pressure of a liquid stream. Compressors are used for the same purpose in gas systems. In this section we are considering liquid flows using *centrifugal* pumps.

Although students have learned about net positive suction head (NPSH) requirements for pumps, they frequently forget about this concept and install a control valve in the suction of a pump. Figure 5 illustrates this forbidden plumbing. Suppose the liquid is coming from the base of a distillation column. This liquid is at its bubblepoint under the conditions in the column. The base of the column must be located at an elevation high enough to provide adequate pressure at the pump suction to prevent the formation of vapor in the pump. This is the NPSH requirement.

If a control valve is installed between the column and the pump suction, the pressure drop over the valve will create a pump suction pressure that violates the NPSH requirements. So control valves in liquid systems should be located downstream of centrifugal pumps. The exact opposite is true for gas systems with compressors, as discussed in the next section.

It should also be remembered that no valves should be used for *positive displacement* pumps. The flowrate of the liquid can only be regulated by changing the stroke or speed of the pump or by bypassing liquid from the pump discharge back to some upstream location. The lower part of Figure 5 illustrates this forbidden plumbing with a positive displacement pump. Throttling a valve in the pump discharge will not change the flowrate of liquid through the pump. It will just increase the pump discharge pressure and raise the power requirement of the motor driving the pump.

Valve Downstream of Centrifugal Compressor

Centrifugal rotary compressors are positive displacement devices. At a fixed speed they compress a fixed volume of gas per time (ft^3/minute).

The mass flowrate of gas depends on the density of the gas at the compressor suction, so changing the suction pressure will change the mass flowrate.

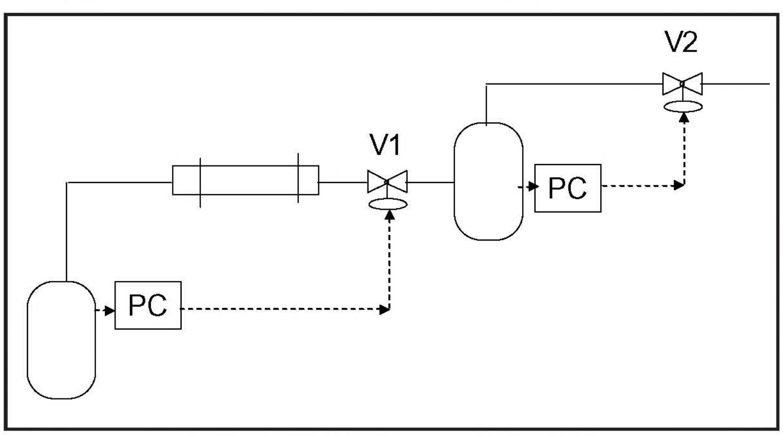

Figure 4. *Two valves in gas-filled line.*

Throttling a valve in the compressor *suction* changes the compressor suction pressure, so it can be used to control the gas flowrate. But throttling a valve in the compressor *discharge,* as shown in Figure 6, does not change the gas flowrate. It just increases the compressor discharge pressure and power requirements.

There are three viable ways to regulate the flowrate of gas in a compression system:

1. *Suction throttling*
2. *Bypass or spill-back from discharge to suction*
3. *Change compressor speed*

The last option is the most energy efficient but requires a variable-speed drive, which is typically a steam turbine if high-pressure steam is available in the plant. Variable-speed electric motors are also available. In compressor simulations this variable-speed option can be easily simulated by manipulating compressor work.

In the discussion above we have considered centrifugal compressors. Regulation of flow through a *reciprocating* compressor can be adjusted by throttling a valve in the suction, by changing

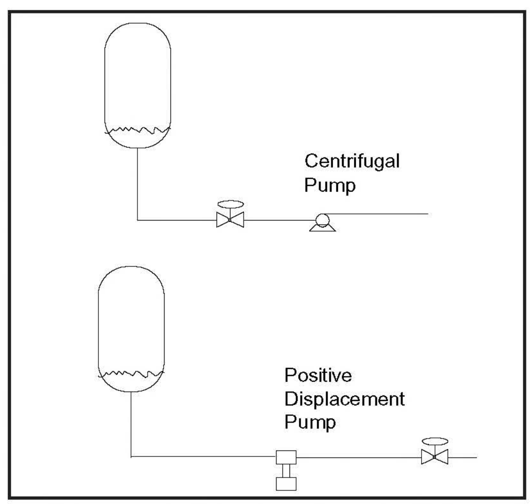

Figure 5. *Forbidden pump plumbing.*

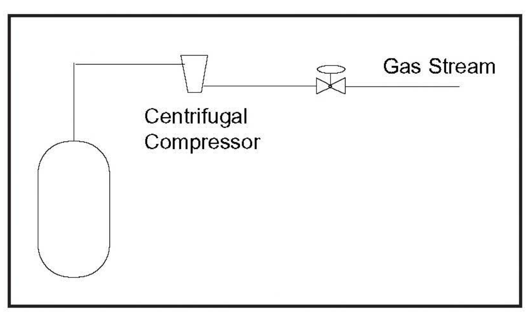

Figure 6. *Forbidden compressor plumbing.*

speed, or by changing the length of the stroke—but not by throttling a valve in the discharge.

Reciprocating gas compressors usually have clearance pockets that change the flowrate slightly, and therefore only provide minor adjustments in flow.

COMMON CONTROL STRUCTURE ERRORS

Most students in a senior design course have had a course in control fundamentals. They have been exposed to the mathematics and to the tuning of single-input, single-output feedback control loops with specified variables to be controlled and manipulated.

To develop a control scheme for a typical process, however, many control loops are required. Decisions must be made about what to control and what to manipulate. Students have had little exposure to this more complex *and* more realistic situation.

The most practical way to learn how to develop a plantwide control system is to examine several realistic examples and step through a logical plantwide design procedure.[5] At Lehigh, several lectures are given early in the second semester discussing reactor control, distillation control, and plantwide control. Then the design groups attempt to develop a control structure for their individual flowsheets. Despite these lectures and reading assignments in the textbook, the students' first efforts at developing a plantwide control system often contain many control-structure errors. Some of the more common are listed below.

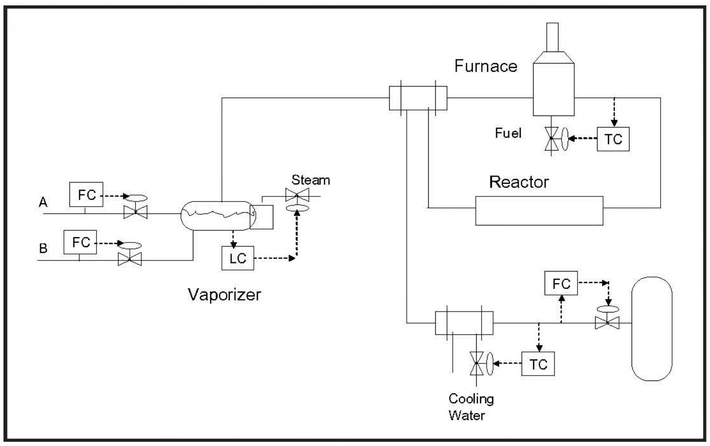

Figure 7. *Flows fixed in and out.*

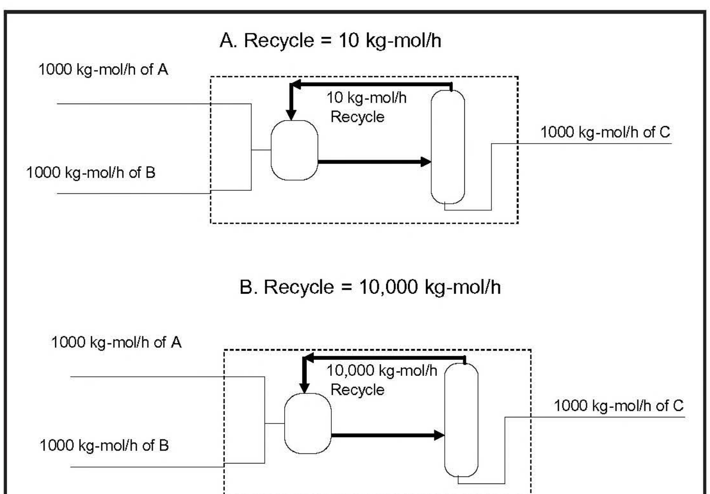

Figure 8. *Recycle independent of fresh feed.*

Fixing Flows Both In and Out

Figure 7 shows a process in which two liquid streams, containing reactants A and B, are fed into a vaporizer. Each stream is flow controlled.

The liquid feeds are vaporized and preheated before entering an adiabatic tubular reactor. Reactor effluent is cooled and fed into a downstream distillation column. The flowrate to the distillation column is flow controlled.

It is obvious that this structure is unworkable. But control schemes like this are proposed year after year by several groups of very capable students. They get wrapped up in the individual unit operations and neglect to look at the big picture.

Similar conceptual issues often occur in specifying recycle streams. Students often have trouble realizing that the flowrate of a recycle stream is completely independent of the flowrate of a fresh-feed stream. Fresh-feed flowrates are set by the production requirements. To produce 1000 kg-mol/h of a product C in a process with the reaction A + B $\rightarrow$ C, the fresh feed of each of the reactants must be 1000 kg-mol/h. Of course, if any reactants are lost as impurities in the streams leaving the unit, the fresh feeds must be appropriately larger. But inside the process we could have a recycle stream of reactant A, for example. As illustrated in Figure 8, the flowrate of this recycle can be anything we want it to be: 10 kg-mol/h or 100,000 kg-mol/h.

Recycle flowrate is completely independent of fresh-feed flowrate.

Liquid Levels and Gas Pressures Not Controlled

Students frequently submit flowsheets in which there is no control of liquid levels in vessels or no control of pressure in gas-filled systems. All liquid levels must be controlled in some way. They can be controlled by manipulating a downstream valve or by manipulating an upstream valve. Of course, the level control schemes for the individual units must be consistent with the plantwide inventory control scheme that connects all the units.

There are very few exceptions to this requirement for controlling all levels. The most common exception is when a solvent is circulating around inside a process and there are no losses of this solvent. In this case there will be a liquid level somewhere in the process that "floats" up and down as the solvent circulation-rate changes. This level is not controlled.

The pressure in a gas-filled system must also be controlled. Gas pressure can be controlled by regulating the flow of gas into or out of the system. It can also be controlled by regulating the rate of generation of gas (*e.g.*, in a vaporizer, in a distillation column reboiler, or in a boiling exothermic reactor). Pressure can also be controlled by regulating the rate of condensation of gas (*e.g.*, in the condenser of a distillation column).

The system can consist of several gas-filled vessels with vapor flowing in series through the vessels. Figure 9 illustrates some of these ideas. In this flowsheet the pressure in the gas loop is controlled by the rate of addition of a gas fresh-feed stream. The pressures in all of the vessels float up and down together, but differ slightly due to pressure drops (which are typically kept quite small to reduce compression costs). The flowrate of the gas recycle stream is flow controlled, using a cascade system: Flow controller output adjusts the setpoint of the turbine speed controller, whose output manipulates high-pressure steam to the turbine.

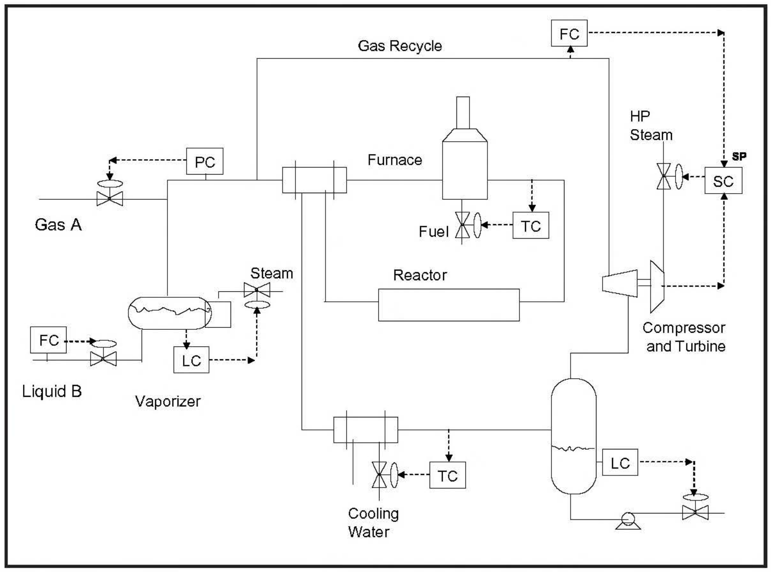

Figure 9. *Pressure in gas loop.*

There are rare occasions when pressure is allowed to float. These occur when it is desirable to keep pressure as low as possible for some process optimization reason (*e.g.*, in some distillation columns where relative volatilities increase with decreasing pressure). In these systems heat removal is maximized to keep pressure as low as possible.

Distillation Columns with a Fixed Product Flowrate

The first law of distillation control says that you cannot fix the distillate-to-feed ratio in a distillation column and also control any composition (or temperature) in the column. This law is a result of the very strong impact of the overall component balance on compositions and the relatively smaller effect of fractionation (reflux ratio, steam-to-feed ratio, etc.) on compositions.

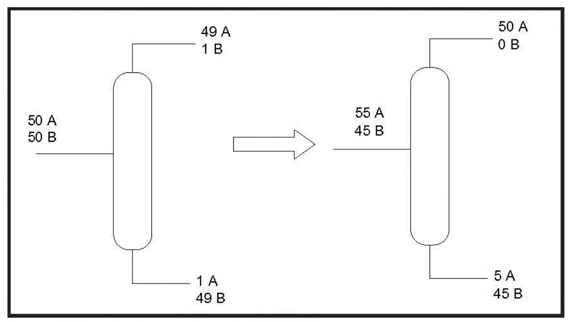

Figure 10. *Fixing product stream in distillation column.*

Figure 10 illustrates the effect of fixing the distillate and bottoms flowrates when changes in feed composition occur. Initially the feed contains 50 mol/h of A and 50 mol/h of B. The distillate contains 49 mol/h of A and 1 mol/h of B, and the bottoms contains 1 mol/h of A and 49 mol/h of B. So product purities are 98 mol%. Then the feed composition is changed so there are 55 mol/h of A and 45 mol/h of B. The distillate and bottoms flowrates are kept constant at 50 mol/hr. Now the distillate will be essentially 50 mol/h of A, and the bottoms will be 5 mol/h of A and 45 mol/h of B. Thus the bottoms purity will drop from 98 mol% B to 90 mol% B. No matter what reflux ratio or reboiler heat input is used, this purity cannot be changed. Controlling a composition or a temperature in the column is not possible.

There are columns in which a product stream is fixed. These are called "purge columns" because the purpose is to remove a small amount of some component in the feed. In these columns, temperature or composition is not controlled. The flowrate of the purge stream is simply ratioed to the feed flowrate.

A somewhat more complex situation occurs when the purging is done in a sidestream column that has three product streams. Consider the sidestream columns shown in Figure 11. The feed stream is a ternary mixture. Two cases are shown. In the column on the left the feed contains a small amount of the lightest component, and it is purged in the distillate stream. The intermediate component is removed in the liquid sidestream.

The distillate is flow controlled, and reflux-drum level is controlled by manipulating reflux flowrate. The issue here is how to manipulate the sidestream flowrate. It cannot be fixed but must change in response to feed composition and flowrate disturbances. The scheme shown in the left of Figure 11 achieves this by ratioing the sidestream flowrate to the reflux flowrate. Temperature or composition can be controlled in this column because the separation between the intermediate and heavy components can be adjusted.

In the column on the right in Figure 11, the feed contains a small amount of the heaviest component, and it is purged in the bottoms stream.

The intermediate component is removed in the vapor sidestream. The bottoms stream is flow controlled, and base level is controlled by manipulating

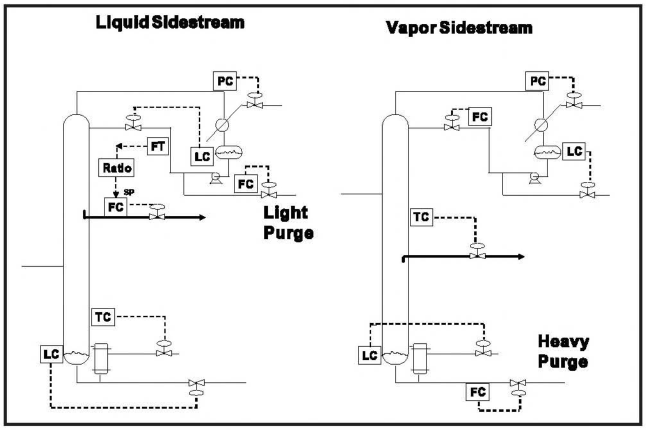

Figure 11. Purge column with sidestream.

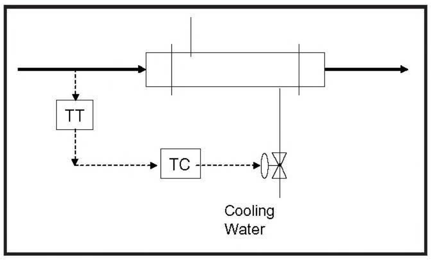

Figure 12. Herron Heresy.

reboiler heat input. The vapor sidestream flowrate, which cannot be fixed, is manipulated to control a temperature in the column. Note that when a small amount of light impurity is present in the ternary feed, a liquid sidestream of the intermediate component is used with its drawoff location above the feed location. This configuration is used because the liquid at the sidestream tray has a lower concentration of the lightest component than the vapor. When a small amount of heavy impurity is present in the ternary feed, a *vapor* sidestream of the intermediate component is used with its drawoff location *below* the feed location because the vapor at the sidestream tray has a lower concentration of the heaviest component than the liquid.

Incorrect Sensor Location and Valves Without Input Signals

Figure 12 shows what we call at Lehigh the "Herron Heresy" (after a senior student in the design course who made the same mistake twice). The diagram shows that the temperature upstream of the cooler is controlled by the flowrate of cooling water to the heat exchanger. This, of course, is impossible and should be obvious. Yet this type of error crops up on several flowsheets every year.

Sometimes students correctly insert a valve in a line to satisfy plumbing requirements, but fail to connect it to a controller. All valves must be positioned by some controller.

Ratioing Reactant Feeds

One of the most important aspects of plantwide control is the manipulation of the fresh-feed streams. A common error is to simply ratio the flowrates of the reactants so as to satisfy the reaction stoichiometry. Although this will work in a simulation study, it will not work in reality.

Flowrates cannot be measured accurately enough to guarantee an absolute matching of the number of molecules of the various reactants. The separation section typically prevents the loss of any of the reactants. Therefore simply ratioing reactants inevitably results in a gradual buildup inside the process of the reactant that is in slight excess.

Some indication of the inventory of the reactants inside the system must be found so that the flowrates of the fresh-feed streams can be appropriately adjusted. Ultimately these flows must satisfy the reaction stoichiometry down to the last molecule. But this much accuracy is way beyond our ability to measure flowrates.

The plantwide control structure in Figure 1 illustrates this principle. The chemistry in this example is the reaction of methyl acetate and butanol to produce butyl acetate and methanol. The reaction occurs in a reactive distillation column (C2). There are two recycle streams. The "LTREC"—the distillate D2 from the reactive column—is an azeotropic mixture of methyl acetate and methanol. The "HVYREC" is the distillate D3 from the third column, which is mostly recycled butanol.

The fresh butanol is added to this recycle stream to control the reflux-drum level in the third column (level controller LC32). This level gives an accurate measurement of the amount of butanol in the system. If more butanol is reacting than is being fed, this level will decrease. On the methyl acetate side, the level in the reflux drum of the first column is controlled by manipulating the fresh-feed stream, which contains methyl acetate and methanol (level controller LC12). This level provides a measurement of the methyl acetate in the system.

Note that the production rate in this plant is set by the flow controller FC1, which controls the feed flowrate D1 to the second column. If more production is desired, the operator increases the setpoint of this flow controller. The increase in D1 also results in an increase in the flowrate of the heavy recycle because of the ratio.

CONCLUSION

Common plumbing and control concept errors have been discussed and illustrated. It is hoped that this paper will help students and engineers avoid these problems in their design projects, and more importantly, in real life. Most of these errors are obvious and can be avoided by using some common sense and not getting all wrapped up in the computer simulation aspects of the problem.

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BIOCHEMICAL ENGINEERING

Taught in the Context of Drug Discovery to Manufacturing

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Biochemical engineering courses are an important part of the chemical engineering curriculum. They introduce students to the rapidly growing field of biotechnology and to the application of chemical engineering principles in the analysis of a nontraditional system.

Typically, biochemical engineering courses begin with the basics of the cell, followed by the basics of cellular machinery, and end with aspects of process design. In the course described here, these traditional topics and concepts in biochemical engineering are taught in a practice-oriented context, using the process from drug discovery to manufacturing as a framework and flowchart for the course. Therefore, each lecture's relevance to the drug-discovery-to-manufacturing process is presented. For instance, students learn how an understanding of the cell is essential for both developing a drug against a disease and for designing a cell-culture process.

The main goal of this biochemical engineering course is to provide a foundation and an overview of the fascinating field of biotechnology and of the role of a chemical engineer, as a scientist *and* a citizen, in implementing this technology. This paper presents

- *Activities for engaging students in learning the biological basics*
- *The drug-discovery-to-manufacturing process*
- *A description of two course projects*
    - *One designed to explore the societal and ethical issues involved in the application of biotechnology*
    - *Another designed to explore the scientific and business aspects of the biotechnology and pharmaceutical industries*

Providing an interesting, relevant, and connected framework for presenting the concepts, and engaging students in learning through in-class activities and projects, are guiding principles applied in the design of this course.[1]

DEFINING THE SCOPE OF THE BIOCHEMICAL ENGINEERING COURSE

At Northeastern University, our biochemical engineering course (CHEU630) is a senior-level, semester-based chemical engineering elective. A fraction of the students have taken high school-level biology but most have not taken college-level biology. As a result, a quarter of this semester-based course—six of 24 lectures—is devoted to covering biological basics, or an understanding of the cell and how it functions. These basics are detailed in the next section (as well as in the course-topic schedule found on the course Web site[2]). Throughout this course, chemical engineering principles such as material balances, transport phenomena, kinetics, and sepa-

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rations are applied either to analyzing biological problems or to designing a cell-culture process.

The scope of this biochemical engineering course is first defined and introduced to the students by using the definition of biochemical engineering found in Shuler and Kargi[3]: "Biochemical engineering has usually meant the extension of chemical engineering principles to systems using a biological catalyst to bring about desired chemical transformations."

In this course, the concept of a biological "catalyst" is interpreted in its broadest sense. For instance, the biological catalyst of choice can be a biological polymer, a cell, an organ, or a whole organism. The spectrum of biological catalysts and the basis for choosing the biological catalyst are presented using Figure 1.

Desired chemical transformations include

- *The production of useful compounds (e.g., vitamins, amino acids, antibiotics, other small-molecule drugs, enzymes, hormones, or antibodies)*

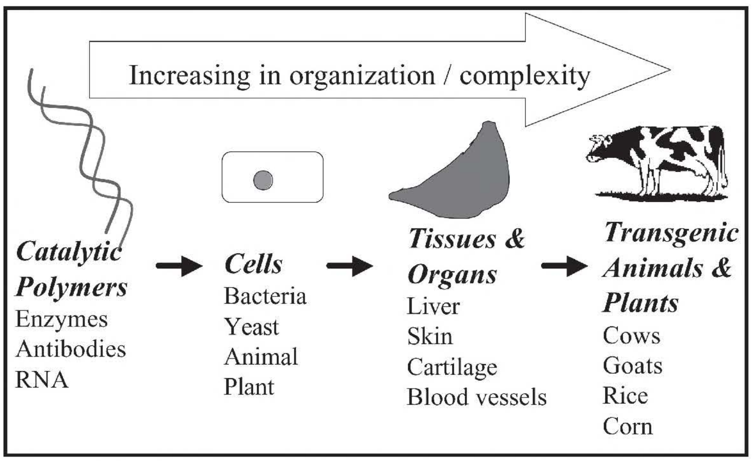


Figure 1. *Biological "catalysts" used for accomplishing chemical transformations.*

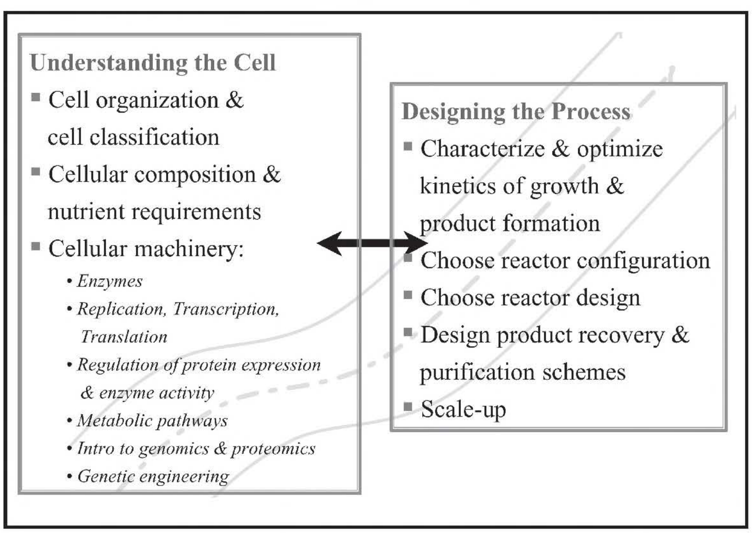


Figure 2. *Course topics taught in context of drug discovery to manufacturing.*

- *The utilization of alternative substrates (e.g., cellulose, lactose)*
- *The degradation of hazardous compounds (e.g., polychlorinated biphenyls or PCBs)*

The biological catalyst is chosen based on the complexity of the desired chemical transformation. In the simplest case, for instance, a chemical transformation can be performed using one or a few specific catalytic biological polymer(s) such as enzymes, catalytic antibodies, and catalytic ribonucleic acids (RNA) or ribozymes. For example, amylase and proteases—enzymes found in detergents—help break down starch-based and protein-based stains in clothing.

If a series of reactions is required to accomplish the desired chemical transformation, we can resort to the enzymatic network housed within a cell by using bacterial, yeast, fungal, animal, or plant cell cultures. Examples include the use of genetically engineered cultures of the bacteria *Escherichia coli* to produce human insulin (by Eli Lilly and Company), or the use of cell cultures of the Pacific yew tree to produce the anti-cancer drug paclitaxel from simple-media components (by Bristol-Myers Squibb Company).

With tissues or organs as the biological catalyst, different cell types are present which together perform chemical transformations (*e.g.*, in the liver) or provide physical structure (*e.g.*, cartilage and blood vessels) not possible with just one cell type.

In the most complex case, a collection of "unit operations" and "reactors" such as those found in a whole animal or green plant may be required. Examples include the use of transgenic cows to produce a therapeutic protein in their milk (by GTC Biotherapeutics), or genetically modified plants containing a vaccine (by ProdiGene, Inc.).

After the spectrum of biological catalysts is introduced through Figure 1, the course focuses primarily on the application of catalytic biological polymers and cell cultures to accomplish the desired chemical transformations.

With the scope of the course defined, a list of course topics and their relationships is then presented using Figure 2. A detailed course-topic schedule with the associated reading assignment is also given to the students and can be found on the course Web site.[2] Students are then introduced to the course flowchart (Figure 2) and shown how the course topics are taught in the context of drug discovery to manufacturing.

Emphasized in this overview and throughout the course is how the design of a process utilizing biological catalysts is intricately dependent on an understanding of the biological catalyst itself. For example, the activity of enzymes is sensitive to environmental conditions including temperature, pH, salts, and solvents. Cells are also not fixed but house their own process control that can change in response to the environmental conditions. As a result, the process design must cater to the needs and health of its biological catalyst for the process to be productive. Thus, a more comprehensive understanding of biological catalysts is necessary and is presented in the course first.

PRESENTING THE BIOLOGICAL BASICS

The biological basics, *i.e.,* an understanding of the cell and how it works, are divided into the following lectures in this course:

- *Cellular organization and cell classification*
- *Cellular composition and cell-culture nutrient requirements*
- *Cellular machinery*

Through in-class activities (presented below) students are involved in considering the impact of biology on the desired chemical transformations and the process design. These in-class activities are intended to help students *make connections* between information in order to draw out concepts rather than simply *memorize* seemingly "unrelated" information.

Cellular Organization and Cell Classification

The goal of this lecture and in-class exercise is to help students understand how the type of cell—*i.e.,* procaryotes vs. eucaryotes, Gram-positive vs. Gram-negative, bacterial/fungal/animal/plant—impacts the types of products formed as well as the design and operation of a process.

The professor can first set the context by discussing the types of cultures applied in industrial processes and the classification of these cultures as procaryotes or eucaryotes. Then an overview of the major differences between procaryotic and eucaryotic cells and the organization within the cell can be presented. The professor can note that choosing the cell-culture system is one of the first steps in developing a cell-culture-based process, thus establishing the relevance of understanding the differences between cell types before choosing an appropriate cell-culture system.

An in-class activity engages students in thinking about the characteristic differences between procaryotic and eucaryotic cells and the implications of these differences. Having read the textbook assignment prior to class, students are asked to make a table with one column listing the characteristic differences between procaryotic and eucaryotic cells, and a second column listing their implications (in terms of the ease of

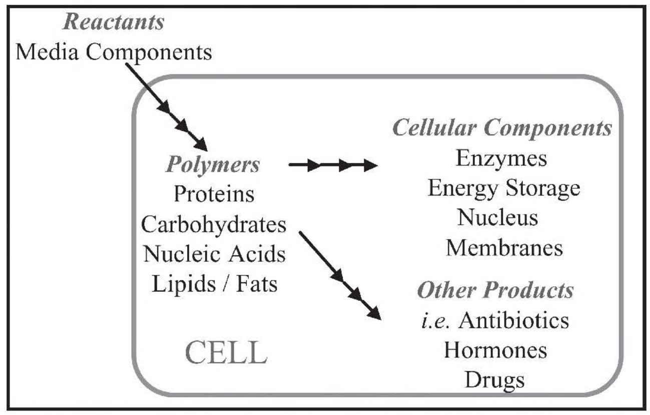


Figure 3. *The conversion of media components into cellular components and other products.*

TABLE 1
Differences Between Procaryotic and Eucaryotic Cells and the Implications of These Differences

Characteristics	Implications
Presence of nuclear membrane (only in eucaryotes)	Affects the ease and applicability of genetic engineering techniques
# of DNA molecules (>1 for eucaryotes)	Affects ease of genetic manipulation since knowledge of gene's function is limited to certain organisms
Type of cell membrane	Affects ease of protein secretion (*i.e.*, the difference between the membrane architecture and protein secretion characteristics of Gram-positive and Gram-negative bacteria)
Cell size	Affects shear sensitivity of cells
Presence of specific organelles (only in eucaryotes)	Allows localization of specific conditions and reactions; allows sequestration of molecules that are toxic to the cell
Specific Examples	
Vacuole	*Sequesters ions such as H^+ and small molecules in plant cells; the recovery of molecules stored in the vacuole can be difficult*
Lysozyme	*Houses digestive enzymes, away from other activities within animal cells*
Chloroplast	*Forms glucose from CO_2 and H_2O in the presence of light in plants; has its own DNA and replicates independently of the cell*
Mitochondria	*Breaks down carbon sources for energy; also has its own DNA and replicates independently of the cell*
Endoplasmic reticulum	*Site of lipid and protein production*
Golgi apparatus	*Site of glycosylation reactions and packaging of proteins*

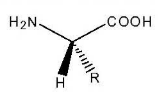
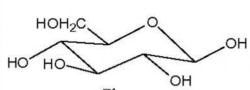
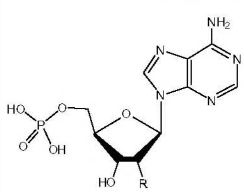
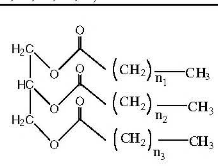
genetic engineering, ease of product secretion, shear sensitivity, or types of products made).

The professor can lead by giving one or two examples and then encouraging the students to work in groups of two to list other examples with the help of their textbook; a sample comparison is shown in Table 1. After about 10 to 15 minutes, the professor can review these differences using a completed table and elaborate on the implications, or the professor can ask students to participate by having them write and review one example on the board.

Specific examples explaining these differences and their implications are given below.

- *One main difference between procaryotes and eucaryotes is the absence or presence of organelles, i.e., specialized compartments with phospholipid membranes that confer selective permeability. These specialized compartments allow different environmental conditions (e.g., different pH, different enzymes, different ion concentrations) to be housed within the cell and hence different types of reactions to occur. For example, protein glycosylation reactions are required for producing an active protein with proper targeting and stability characteristics. These reactions take place in the Golgi apparatus and the endoplasmic reticulum after the initial protein is formed in the cytoplasm. Hence, the implication is that eucaryotic cell cultures would be the biological catalyst of choice if the desired product were a glycosylated protein.*
- *Another example of the importance of cell type on the process is the use of Gram-positive versus Gram-negative bacteria. Since Gram-positive bacteria have a single outer membrane, proteins are more likely to be secreted using this type of bacteria than with Gram-negative bacteria. Hence, the implication is that Gram-positive bacteria would be preferable since the recovery of a secreted protein is more cost-effective than the recovery of an intracellular protein.*
- *Differences in the size of the cell have implications on the operation and scale-up of a bioreactor. For example, due to their smaller size, bacteria are more resistant to shear than animal or plant cells and can be grown in a highly agitated, aerated stirred tank rather than requiring a specialized bioreactor.*

TABLE 2
Chemical Structure, Function, and Composition of Monomers/Polymers in the Cell

Monomer / Polymer	Chemical Structure (Elemental Composition)	Function / Localization in the Cell	% of Polymer[5]
Amino acids / Proteins (20 amino acids)	 R = functional group Illustrate primary, secondary, tertiary, quaternary structure (C, H, O, N, S)	Functions include physical structure, regulatory (as hormones), catalytic (as enzymes), transport (as membrane pumps), & protective (as antibodies); protein are localized in membranes & in the cytoplasm & throughout the cell	50% by dry wt
Monosaccharides / Polysaccharides or Carbohydrates	$C_n(H_2O)_n$  Glucose (C, H, O)	Functions as energy storage molecules, structural component of cell wall, component of DNA & RNA, component of glycosylated proteins which is important for protein targeting & stability	15 -35%
Nucleotides / RNA & DNA	 R = H → DNA R = OH → RNA (C, H, O, N, P)	Functions as molecules for energy storage (ATP), for encoding the cell's characteristics (DNA), for encoding instructions for protein production (RNA); localized in the nucleus, in organelles such as mitochondria & chloroplasts, and in the cytoplasm as t-RNA, mRNA, r-RNA.	10 – 20%
Fatty acids / Lipids or Fats	 (C, H, O)	Functions as energy storage molecules, regulatory molecules (hormones), and components of the cell membrane (composition affects the membrane's permeability characteristics)	5 – 15%

Cellular Composition and Cell-Culture Nutrient Requirements

The goal of this lecture and in-class activity is to help students link the cell-culture nutrient requirements to the cellular composition and to the desired products formed. Figure 3[4] is first used to depict the cell as the ultimate alchemist: It begins by transforming simple raw materials in media such as sugars and amino acids into biological polymers (*e.g.,* proteins, carbohydrates, nucleic acids, lipids, and fats); those polymers then either make up the cell (*e.g.,* phospholipid membranes, enzymes, nucleus, and energy storage such as glycogen and starch) or are converted into valuable complex bioactive molecules/polymers (*e.g.,* vitamins, amino acids, antibiotics, other small-molecule drugs, enzymes, and antibodies). Stated simply, the student's role as the biochemical engineer is to maintain healthy cell cultures and coax them to make the desired product.

The optimization of growth and product media is therefore one aspect of process development for maintaining viable and productive cell cultures. With this context, students are then asked to consider the monomers/polymers that make up the cell and deduce the nutrients in the medium needed for making these essential monomers/polymers.

For example, students are asked to make a table with headings shown in Table 2, listing the major monomers/polymers that make up the cell, their chemical structure and elemental composition, their function or localization in the cell, and their percent composition in the cell.

Similar to the previous in-class exercise, students should have read the assignment prior to class and are then encouraged to work in pairs to complete the rest of the table with the help of their textbook. Again the professor can lead by giving one or two examples first. After about 10 to 15 minutes, the professor can either review and elaborate on this material using the completed table, or have each pair of students participate by writing and reviewing one example on the board.

Based on the composition of these polymers in the cell (Table 2), students are then asked to determine the important elemental macronutrients—*e.g.,* C, H, O, N, P, S, etc.—and to order the expected prevalence of these macronutrients in the culture medium. Students can then confirm their answers by studying the medium compositions of bacterial, yeast, animal, and plant cell cultures,[6] *i.e.,* that the carbon source is supplied at the highest concentration. They can also compare the differences in the medium compositions of these cell cultures, and learn about the appropriate form to supply these nutrients. For instance, sulfur is fed as a sulfate salt in plant cell culture medium, but in animal cell cultures it's in the form of amino acids (cysteine and methionine).

Two points should be emphasized and connected:

- *The main media components provide the carbon backbones, or skeletons, for making the main cellular polymers, the product of interest, and the energy sources for the desired chemical transformations.*
- *The media also contains micronutrients (e.g., various metal ions, hormones, and vitamins) and inducers which are critical for maintaining the culture health and for inducing or directing the cellular activities toward growth or product formation.*

Hence, medium optimization involves more than just closing the material balance between inputs (media components) and outputs (cellular polymers, desired products). It requires an understanding of the cellular machinery involved in these chemical transformations and the application of that knowledge (such as by the addition of hormones or inducers) toward directing those cellular processes appropriately.

The main goal of this biochemical engineering course is to provide a foundation and an overview of the fascinating field of biotechnology and of the role of a chemical engineer, as a scientist and a citizen, in implementing this technology.

Cellular Machinery

At this point in the course, students have gained an understanding of: (1) how the selection of cell type/culture affects the kind of product made or the design of the process, and (2) the importance of the medium composition on growth and product formation. Next, the course addresses (3) how the cell makes the biological polymers and the desired products, and (4) how the cell regulates which and how much of these products to make. The inner workings of the cell, *i.e.,* its cellular machinery, are then covered in the order shown in Figure 2 (or see the more detailed course-topic schedule). The tools used in genomics and proteomics are then presented as the current approach to probing and expanding our understanding of the cellular machinery. Once the basics of cellular machinery are covered, the tools of genetic engineering are introduced as a means of altering the native, existing cellular machinery to either: produce a new protein previously not made by that cell culture, or enhance or inhibit the production of an existing protein.

Examples from the biotechnology and pharmaceutical industries are used to show the application of these topics to understanding disease mechanisms, to discovering and designing drugs to target a disease, and to enhancing the production of biological compounds from cell cultures. Examples are drawn from various sources such as those noted in the following sections on the drug-discovery-to-manufacturing process and on the survey of a biotechnology or pharmaceutical company.

PRESENTING AN OVERVIEW OF DRUG DISCOVERY TO MANUFACTURING

Before embarking on the engineering aspects of designing a cell-culture process, the path from drug discovery to manufacturing is presented in one lecture. Although the course is taught using the drug-discovery-to-manufacturing framework, a greater understanding of its overview was achieved when it was presented *after* covering the biological basics. This lecture also illustrates the multidisciplinary effort involved in discovering and bringing a drug to market—highlighting the role and contribution of chemical engineers to this endeavor.

The topics covered include

- *Ways that drugs intercept the biochemical pathway of the disease (e.g., by interfering with such biochemical steps in the cell as receptor-ligand binding, signal transduction, transcription, translation, or enzyme activity)*
- *Ways that drug hits are discovered or screened using whole-cell assays or target assays*
- *Sources of these drug molecules (e.g., natural-product libraries, combinatorial chemistry libraries, targeted synthesis, drug modeling)*
- *The goals and steps involved in the initial testing of a drug's effectiveness or safety (e.g., characteristics such as adsorption, distribution, metabolism, excretion, and toxicology)*
- *The goals of the new investigational drug application (IND), the new drug application (NDA), and the different clinical trials (e.g., Phase I, II, III)*
- *Steps involved in developing a cell-culture process*
- *Cost and time associated with the drug-discovery-to-manufacturing process and the likelihood that a drug hit becomes a prescribed drug*

Web sites for the Food and Drug Administration (FDA),[7] the Pharmaceutical Research and Manufacturers of America (PhRMA),[8] and various pharmaceutical/biotechnology companies provide publications, examples, and resources for these lectures. For example, an FDA publication, *From Test Tube to Patient: Improving Health Through Human Drugs*,[9] presents an overview of the drug-development process.[10] In addition, the FDA Web site provides drug information such as a drug's chemical structure, the mechanism of the drug in targeting disease, use of the drug, and its side effects.[11] A final project on surveying a pharmaceutical or biotechnology company (covered later in this paper) also provides examples of how specific drugs work and how they are made.

PROJECT ON SOCIETAL AND ETHICAL IMPACTS OF BIOTECHNOLOGY

Project Description

Scientists and engineers need to understand the impact of their discoveries and technologies on society. Our students are the future scientists and engineers who will be involved in determining the policies that regulate (*i.e.*, promote and restrict) these discoveries and technologies for the benefit and protection of society. In this project, students choose a contemporary bio-related technology under debate, and evaluate the issues regarding the application of this technology. Serving as an advisory board, students weigh the societal and ethical impacts of a specific biotechnology and then propose their recommendations on its appropriate use in written form. Contemporary biotechnologies that have raised concerns regarding safety and/or ethics are

Scientists and engineers need to understand the impact of their discoveries and technologies on society. Our students are the future scientists and engineers who will be involved in determining the policies that regulate . . . these discoveries and technologies for the benefit and protection of society.

listed and can be introduced using Table 3. References from news and popular-science magazines such as *Time* and *Scientific American* are also listed in Table 3 and can serve as a starting point for this project.

Project Specifics

Students, working in groups of two or three, research, brainstorm, and debate the issues behind the use of their chosen bio-related technology and then present their evaluation in written form as an editorial (five pages maximum). In evaluating the technology of interest, they are first asked to (1) briefly explain the science behind the technology, and (2) summarize the benefits, risks/drawbacks, and other issues, noting if these issues are hypothetical or real. Finally, they are asked to synthesize their proposal on the application of this technology by (3) presenting an argument for or against the application of the technology of interest and the conditions under which the technology should be limited, and (4) formulating their recommendations on the application of this technology. Posted on the course Web site[12] are sample student reports exploring the societal and ethical impacts of two such technologies: genetically modified crops and cloning.

Several ABET criteria[13] are covered through this project: Students investigate a contemporary issue (Criterion 3j); evaluate the societal and ethical impacts of biotechnology (Criterion 3h); work in a team consisting of members with potentially different views (Criterion 3d); and practice communicating their evaluations effectively and logically (Criterion 3g).

TABLE 3
Topics for Exploring the Ethical and Societal Impacts of Biotechnology

Debated Biotechnologies	References
Human cloning Since the cloning of Dolly (the sheep), society has speculated that the reproductive cloning of humans was just a matter of time. While many are opposed to the reproductive cloning of humans, the use of therapeutic cloning remains highly debated. The goal of therapeutic cloning of human cells is to generate stem cells, *i.e.*, cells which give rise to new tissue and organs. Both types of cloning utilize a similar technique which starts with an egg and the replacement of its nucleus. Will therapeutic cloning yield replacement parts for damaged organs or serve as the precursor to reproductive cloning?	[17, 18]
Genetic alterations in human embryos The science fiction movie *GATTACA* portrays a society where genetically engineered babies are the norm while babies born by natural means become the discriminated, or the untouchables, of society. With the human genome already sequenced, gene sequence(s) which code for a devastating disease can potentially be corrected. Could this lead to the elimination of diseases or the age of designer babies?	[19 - 24]
Genetically modified crops (GMCs) Crops such as rice, soybeans, corn, and potatoes have been genetically engineered to enhance their yield, nutritional content, resistance to diseases or pests, or tolerance to specific environmental conditions such as drought or soil salinity. Crops have even been genetically engineered to produce therapeutics such as vaccines. Could this be the solution to world hunger or to the high cost of pharmaceuticals and biological compounds?	[25 - 30]
Transgenic animals Animals such as cows, goats, or chickens have been genetically engineered to produce therapeutics in their milk or eggs. It has been suggested that producing therapeutics through animals may be far more economical than through cell cultures in bioreactors. Fish such as salmon have also been genetically engineered to be fast-growing to satisfy the growing appetite of consumers for fish. Could transgenic animals be the solution to the high cost of pharmaceuticals and biological compounds?	[31]
Availability, patent, and ownership of genetic sequences The genome of several organisms has been sequenced. Determining what each gene codes for is the next task. Who has the right to own or benefit from these gene sequences? Should genetic tests be required or elective? Particularly with the human genome, should the genetic sequences of individuals be made available and if so, to whom?	[32 - 36]
High cost of pharmaceutical drugs The high cost of some pharmaceutical drugs has made them unaffordable to those in the U.S. and in Third World countries. What contributes to the high cost of these drugs? How can these drugs be made available to those who need them without crippling the companies that discover and produce these drugs?	[37 - 39]

The scope of this biochemical engineering course is first defined and introduced to the students by using the definition of biochemical engineering found in Shuler and Kargi[3]: "Biochemical engineering has usually meant the extension of chemical engineering principles to systems using a biological catalyst to bring about desired chemical transformations."

This project is assigned on the first day of class since students are already acquainted with these debated issues in the news. The project is only to be completed after the biological basics have been covered in class (see course-topics schedule). The project comprises 10 percent of the course grade and is graded equally on two components:

- *The quality and completeness of their evaluation of the technology (i.e., in terms of the science and the issues pertaining to this technology)*
- *The support for and the logical presentation of their recommendations for the application of the technology of interest*

PROJECT SURVEYING A BIOTECHNOLOGY OR PHARMACEUTICAL COMPANY

Project Description

Students survey a company of interest—potentially a company in which they are seeking employment—to learn more about the scientific and business aspects of the biotechnology and pharmaceutical industries. The goals of this project are

- *To illustrate that a company has an underlying scientific platform or approach for targeting a disease*
- *To demonstrate how an understanding of biology is critical to determining a treatment for intercepting a disease*
- *To gain a sense of the time and resources invested in researching a disease and in developing a drug or treatment for that disease*
- *To prepare students for a job interview*

Resources for this project include company Web sites, company annual reports, *Chemical & Engineering News,* news periodicals, technical journals, and the FDA Web site.[11] Other references such as medical dictionaries, biology textbooks, or anatomy and physiology textbooks, will be useful for understanding and addressing the question of how the drug targets the disease.

The company surveys from individual students can then be compiled in a notebook or file for the entire class to use in their job searches. An example of one student's survey on Genentech has been posted on the course Web site.[14]

Project Specifics

In surveying a company, students research the following questions (presented in a handout):

- ► *What is the company's mission or approach? For instance, does the company target specific diseases such as cancer or those that affect the immune system? What is the company's platform or technology for targeting diseases or for discovering drug leads?*
- ► *List examples of research areas. Are they related? Generally, a great deal of research in the basic sciences is required to understand a disease or develop a drug compound for targeting that disease.*
- ► *List the important accomplishments in the company's history that may have helped them become established as a biotechnology or biopharmaceutical company.*
  - *For example, companies may start as drug-discovery companies and license their discoveries to another company for manufacturing. As more of their drugs make it to market, these companies evolve into bigger entities and eventually build their own production facilities. Genentech is such an example.*[15]
  - *Another example is Pfizer, a company that was not initially involved in fermentation. Before 1939, Pfizer was producing citric acid from lemons.*[16] *When the price of lemons increased dramatically, it was no longer economical to extract citric acid from lemons and Pfizer pursued an alternate means of producing citric acid using mold. By turning "lemons into lemonade," Pfizer became well-positioned for the large-scale fermentation required to produce penicillin from mold during World War II.*
- ► *List two products that are already being marketed by the company. What is each product used for? How does each product work, i.e. its mechanism for targeting the disease? What type of drug is it? How is it made, i.e. from genetically engineered*

Continued on page 221

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 fourteen double-spaced pages and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

'GREENING' A DESIGN-ORIENTED HEAT TRANSFER COURSE

Ann Marie Flynn, Mohammad H. Naraghi, Stacey Shaefer
Manhattan College • Riverdale, NY 10471

The focus of this work is to demonstrate how green engineering concepts and principles can be incorporated into a predominantly design-oriented heat transfer course through the utilization of a heat transfer problem set that was developed with the support of the U.S. Environmental Protection Agency (EPA) for a project at Rowan University entitled "Green Engineering in the Chemical Engineering Curriculum."

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***Stacey Shaefer** is a chemical engineering student at Manhattan College. After receiving her B.S. in May 2005 she will begin her studies in Manhattan College's Seamless Masters Program in September 2005 and expects to receive her M.S. in May 2006. (Photo not available.)*

Although the EPA was created in the early 1970s and environmental regulations have been around since the mid 1960s, the concept of green engineering did not gain prominence until the mid 1990s.[1] Green engineering has been described as the incorporation of environmentally conscious attitudes, values, and principles into engineering design, toward a goal of improving local and global environmental quality.[1, 2] This work examines the incorporation of key green engineering concepts outlined in *Green Engineering—Environmentally Conscious Design of Chemical Processes,* by Allen and Shonnard, with a variety of topics found in the widely used heat transfer textbook, *Fundamentals of Heat and Mass Transfer,* by Incropera and DeWitt.[3, 4] To cover topics found in 13 chapters in the Incropera and DeWitt text, 24 problems were developed for a junior-level chemical engineering class. A sample of some of the more popular problems is presented here.

DEVELOPMENT

The undergraduate chemical engineering program at Manhattan College focuses heavily on design. One of the primary goals of the course is to prepare the senior students for a two-semester plant-design sequence. Typical design elements include the calculation of conduction and convection resistances, overall heat transfer coefficients, and standard heat exchanger design such as double pipe and shell and tube. Initially, the logistics of incorporating additional concepts such as green engineering principles into an already packed course appeared unrealistic. During the development of the problem set, *typical* questions arose, such as, "How do you green a shell-and-tube heat exchanger?" As a result, *typical* answers followed, such as, "Increase the heat recovery, use better insulation." In order to capture the attention of the students, it was concluded that a *less typical* approach was needed. Therefore, the resulting problem set focused less on greening the fundamentals of heat transfer design and more on examining the environmental impact of the design. Each problem in the set contains multiple parts; the early parts address standard, necessary design concepts required by a design-oriented curriculum, while the latter parts examine the incorporation of green engineering principles into the design.

Therefore, the problems could be used in two ways.

► ***Plan A.*** *The problems could be used in their entirety as a vehicle to both reinforce design concepts presented in class and introduce the student to green engineering concepts.*

► ***Plan B.*** *If the design concepts in the problems did not coordinate well with the class material, the green engineering portions of the problem could be used alone to illustrate the incorporation of green engineering into a heat transfer course.*

For this study, the first half of the semester followed Plan A. After a midterm assessment of the newly greened course, the mode of operation was switched to Plan B. Each greened heat transfer problem references the following: the corresponding heat transfer section(s) in Incropera and DeWitt, the corresponding section(s) in the green engineering text by Allen and Shonnard, and the specific Sandestin green engineering principles covered.[3, 4, 5] The entire problem set with solutions, as well as a detailed mapping of the green engineering principles into the heat transfer course, can be found at <www.rowan.edu/greenengineering>.

Over a 14-week semester, 27 students were given eight homework assignments that totaled 27 problems. Of the 27 problems, 11 problems (approximately 40%) were taken from the newly developed greened heat transfer problem set. A variety of student surveys were used to assess the greened heat transfer problems and the incorporation of green engineering principles into the course. In addition, students were required to individually submit two-page reaction papers at the end of the semester outlining how (if at all) the greened heat transfer problems increased their awareness of green engineering. Four of the greened problems that received the more positive feedback from students are presented here.

PROBLEM 1

The Conduction Shape Factor and the Importance of Rain Forest Conservation

Incropera & DeWitt: 4.3; Allen & Shonnard: 1.7; Green Engineering Principles: 2, 5

Problem Statement

Faced by what is perhaps Ecuador's severest economic crisis of this generation, the government of Ecuador has come up with a plan to double its export of oil. Construction of a new, above-ground oil pipeline, the OCP (Oleoducto de Crudo Pesado, or Heavy Crude Pipeline) will make it possible to open up vast new areas of the Amazon to oil exploration. Efficient transportation of the crude requires that the temperature of the crude remain above its pour point. Below its pour point of 35°C, the crude takes on a waxlike consistency. The crude enters the OCP at 70°C. The temperature is monitored until it begins to approach its pour point ($T_{oil} \approx 40°C$) at which point steam is injected to raise the temperature of the crude back up to 70°C. This proposed pipeline will pass through 11 natural reserves and "protected" areas. Schedule 80 pipe (12-inch) is used to transport 840,000 gal./day of crude. Assume the average temperature of the ambient air is 30°C ($h = 6\ W/m^2$-K). The following crude oil data is available:

$$c_p = 2047\ J/kg\text{-}K$$

$$\nu = 0.839E\text{-}04\ m^2/s$$

$$\rho = 0.864E03\ kg/m^3$$

$$k = 0.140\ W/m\text{-}K$$

$$Pr = 1050$$

(a) Compare the distance between steam injections for an uninsulated pipe to a pipe that is insulated with 3-inch standard fiberglass insulation (k = 0.035 W/m-K).

(b) This proposed pipeline will pass through 11 natural reserves and protected areas. What are the environmental hazards associated with invading these rain forests and protected areas in order to build this pipeline?

(c) What are the dangers associated with building this pipeline if it is to pass through cities and near local water supplies? Since this area sustains many earthquakes, landslides, and soil shifting, what would be the consequences of a pipeline rupture?

Problem Solutions

Part (a) of the problem would be considered a typical design question found in any homework or on any exam. The student is required to calculate how far the crude will travel in the pipe before the temperature drops from 70° to 40°C—approximately 5°C above its pour point. The student finds that without insulation, steam must be injected every 17 km. When the pipe is insulated with 3 inches of standard fiberglass insulation, steam must be injected every 117 km. This is an ideal problem to solve with packaged software such as Mathcad, as it allows the student to easily experiment with insulation thicknesses. The student can find that as little as 1 inch of fiberglass insulation will increase the distance between steam injections by almost 400% (from 17 km to 65 km)—critical information when the crude pipeline is located in areas uninhabitable for workers, or regions difficult to access. The crude oil data is courtesy of Conoco-Phillips.

The solutions to parts (b) and (c) required the student to perform a library and/or Internet search.[6, 7] The results were astounding. First, the students (those previously unaware) became aware of the enormous wealth of natural resources found in a rain forest. Such resources include: Of the 121 prescription drugs sold worldwide that come from plant-derived sources, 70% of these plants come from rain forests; 80% of the developed world's diet originated in the tropical rain forest, including many fruits, vegetables, and nuts; and 70% of the 3,000 plants that are active against cancer cells are located in rain forests. The students were so impressed with the essential world service provided by a rain forest, that simply being required to list the dangers associated with a ruptured pipeline (*e.g.*, destruction of human life, aquatic life, and wildlife; rain forest damage; and loss of potable water) sparked shock and disbelief among them. The instructor should be made aware to set aside extra class time for discussion when the solution to this problem is reviewed.

This problem could easily be converted to a take-home problem, individual project, or group project with an oral presentation. Given the real economic crisis that currently exists in Ecuador, the students might be asked to provide a viable, alternate solution—complete with a hazards and operability study (HAZOP) or a hazards analysis (HAZAN, a process used to determine how a device can cause hazards to occur and how the risks can be reduced to an acceptable level). This would require students to weigh "real" economics with environmental impact.[8]

PROBLEM 2

Natural Convection and Energy-Efficient Lighting

Incropera & DeWitt: 9.6; Allen & Shonnard: 1.3; Green Engineering Principles: 1, 5, 6

Problem Statement

Lighting directly affects our economy. As a nation, we spend approximately one-quarter of our electricity budget on lighting—or more than $37 billion annually. An incandescent light bulb is highly inefficient because it converts only a small amount of the electrical energy into light; the rest is converted to heat. In spite of this inefficient conversion of energy, the relatively inexpensive purchase price of incandescent bulbs when compared to fluorescent lighting accounts for their popularity among consumers.

A 75W bulb that is assumed to have the shape of a sphere has a diameter of 6 cm and a surface temperature of 250°C (when the light is turned on). The surrounding room air temperature is 25°C.

(a) Determine the rate of heat transfer from the incandescent light bulb to its surroundings.

(b) Compact fluorescent light bulb products generate approximately 70% less heat than standard incandescent lighting. Determine the rate of heat transfer from the fluorescent bulb to the surrounding air.

(c) Explain why fluorescent lighting might be preferred over incandescent lighting from an environmental perspective.

Problem Solutions

Parts (a) and (b) of this problem are typical heat transfer design problems. The students are required to make reasonable assumptions (*e.g.*, steady state conditions, air is an ideal gas). The students are required to use a free-convection correlation for spheres, such as the Churchill correlation

$$\left(\mathrm{Nu} = 2 + \frac{0.589 \cdot \mathrm{Ra}^{1/4}}{\left[1 + (0.469/\mathrm{Pr})^{9/16}\right]^{4/9}} \right)$$

to determine the convection heat transfer coefficient used to calculate the heat transfer rate via natural convection from the bulbs to the air. The radiation heat loss from the light bulb can be evaluated via

$$Q = A\varepsilon\sigma\left(T_s^4 - T_{air}^4\right)$$

Many of the physical properties necessary for the calculations may be found in the appendices of Incropera and DeWitt. The students determined that the rate of heat transfer from the incandescent bulb was approximately 65.13W compared to 19.54W from the fluorescent bulb.

Solution to part (c) of the problem required the students to look outside of the class notes and textbook—namely to the library and/or Internet.[9] Many students found this problem interesting because they were so familiar with the topic and because their curiosity was piqued at the cost-saving prospects. Students found that not only was the fluorescent bulb more efficient in converting electrical energy to light, but that one Energy Star-qualified fluorescent bulb could reduce greenhouse gas emissions by more than 500 lbs. over its lifetime (which is equivalent to saving 445 lbs. of coal from being burned to generate electricity). Also, since fluorescent light bulbs produced significantly less heat than incandescent bulbs, they were significantly cooler to the touch and eliminated many safety issues when used in the home. Students also found that even though the fluorescent bulb was more expensive than the incandescent bulb, it had a significantly longer lifespan than the incandescent bulb (the lifespan of each bulb varied from manufacturer to manufacturer, but a 75W incandescent bulb averaged 750 hours and a 75W fluorescent bulb averaged 10,000 hours). Students were given extra credit if they performed a simple cost comparison for the two different light bulbs used in a typical home in a five-year period. It was found that the light bulb cost for a typical home decreased by approximately 53% over a five-year period when fluorescent bulbs were used in place of incandescent bulbs.

PROBLEM 3

Natural Convection Through Windows and Life-Cycle Studies

Incropera & DeWitt: 9.8; Allen & Shonnard: 13.5; Green Engineering Principles: 2, 3

Problem Statement

In Coldest Small Town, U.S.A., a new homeowner who has recently purchased her home has a 25-year mortgage attached to it. Her first decision regarding this new home is to purchase new double-pane vinyl replacement windows to replace the single-pane wood windows currently in place. The house has a total of 25 windows that are 30 inches by 32 inches. The homeowner cannot decide if it would be more cost efficient for her to replace her old windows with standard (air-filled) double-pane windows or if she should upgrade to argon-filled double-pane windows. The double-pane windows have two pieces of glass separated by a one-inch-wide spacing. In winter, the glass surface temperatures across this space are measured to be –15°C and 20°C. The home is heated by natural gas at a cost of \$0.4/MJ. The heat is used for four months per year, 24 hours per day, seven days per week. The cost for the standard air-filled window is \$325. The cost for the argon-filled window is \$400. The rate of heat loss through one of the current single-pane windows by natural convection is 65W at the indicated temperatures.

(a) Determine the rate of heat transfer by natural convection through one standard double-pane window.

(b) Determine the rate of heat transfer by natural convection through one argon-filled window.

(c) Assume this homeowner will remain living in this house for the full 25-year mortgage. Determine which double-pane window she should purchase by doing a life-cycle study on the windows. The system boundary that should be used for this study is the life of the windows while they are installed in the home.

(d) Compare the life cycle of the old wood windows to the life cycle of the new vinyl replacement windows. The system boundaries that should by used for this study are the complete life cycles of each product.

Problem Solutions

Once again, the solution to parts (a) and (b) were typical of natural-convection problems found in an undergraduate heat transfer class. The student is required to make reasonable assumptions (*e.g.*, steady state, negligible radiation effects), calculate a natural convection heat transfer coefficient using a Nusselt number correlation, and determine the heat loss from the air-filled double-pane windows (part a) as well as from the argon-filled double-pane windows (part b). The student discovers that the heat loss is reduced by approximately 35% when switching from the air-filled windows (51W) to the argon-filled windows (33W). Even though parts (a) and (b) of this problem may appear fairly typical, many students had additional comments regarding energy loss. Some of the comments included: that choosing the correct window is negated by the additional heat loss resulting from improper installation of the windows, that choosing the correct window is more or less important depending on the climate, that the difference in quality from one manufacturer to another must also be accounted for, and that the pros and cons of upgrading from vinyl windows to high-end manufacturers such as Anderson and Pella should also be examined.

In order to complete parts (c) and (d) of this problem, it is necessary for the instructor to review the concept of life cycles from the green engineering text beforehand since it is not ordinarily part of a typical heat transfer course. The results of the life-cycle study highlight for the student the environmental impact of the replacement windows via the significant reduction in energy consumption. Over a 25-year period, this energy reduction translates to a savings of approximately \$25,000 for the air-filled windows and approximately \$68,000 for the argon-filled windows. A library/Internet search shows that vinyl replacement windows have a longer lifespan when compared to single-pane wood windows and finally, most of the vinyl from the window is recyclable at the end of its use.[10]

PROBLEM 4

Radiation Heat Provides Comfort for the Workers and Productivity for the Company

Incropera & DeWitt: 13.3; Allen & Shonnard: 9.2; Green Engineering Principles: 1, 2

Problem Statement

A maintenance hangar facility for aircraft recently installed four gas-fired infrared tube heaters above the main work area in the hangar. These heaters were installed to provide a more comfortable environment for the workers as early-morning temperatures in the hangar can reach as low as 40°F. During the colder seasons, temperatures can get as low as 28°F in the hangar. Each of these industrial heaters radiate heat at a total rate of 5,118 BTU/hr (1500W). Assume, however, that only 5% of this heat directly reaches the workers in the hangar. There are 20 maintenance workers who work in this area each day. The average worker has an emissivity and absorptivity of 0.90 and 0.95, respectively, and an exposed surface area of approximately 18 ft^2. These workers are generating heat at an average rate of 30 BTU/hr (30% of which can be considered sensible heat—the heat absorbed or transmitted by a substance during a change of temperature which is not accompanied by a change of state). The convection heat transfer coefficient for the surrounding air is 1.585 BTU/hr-ft^2 R.

Assume that the workers can remain comfortable with an exposed skin temperature of 85°F and the workers' clothing has an average resistance to heat transfer of 0.880(R-ft^2-hr)/Btu. The outside temperature of the workers' clothing is typically 10°F above the surrounding air temperature.

(a) Are the four radiant heaters enough to keep the workers comfortable during the coldest mornings?

(b) Explain why it might be considered good practice for the company to install these radiant heaters in the hangar.

Problem Solutions

This was a fun, relatively short problem. Before the problem was distributed to the students, the question was posed, "You have these 20 people working in an airplane hangar, the dimensions of which can be measured in acres! What are you going to do—heat the whole thing?"

Many solutions from reasonable (localized space heaters) to impractical (chemically heated overalls, similar to hand and foot warmers used by skiers) were suggested by the students. When the students were told that the answer lay in the form of radiant heat transfer design, simply because the radiant heat will warm the objects and not the air, this often-maligned topic in the curriculum seemed to get a temporary stay of execution (at least from the course-objectives survey). This problem provided an interesting, practical application for radiation heat transfer.

For part (a), the student is required to make reasonable assumptions (*e.g.*, steady state, constant properties, air motion in the hangar is negligible, workers are small compared to uniform temperature surroundings). The students must then perform an energy balance on the workers where

$$\{E_{\text{in from the heaters}}\} - \{E_{\text{out from conv \& radiation from the bodies}}\} + \{E_{\text{gen from sensible heat}}\} = 0$$

to solve for $T_{\text{surroundings}}$ by either trial and error or use of a software package such as Excel. The students are required to calculate an overall heat transfer coefficient that takes into account the resistance due to clothing. It is found that the four radiant heaters provide enough heat to keep the workers comfortable to a minimum surrounding temperature of 12.8°F, which is approximately 15°F below the minimum temperature experienced.

Part (b) of the problem outlined a situation where the student was required to focus more on the human aspects of optimal heat transfer design and less on dollars and cents. Results showed that the lost time for the workers was expected to decrease, the productivity of the workers was expected to increase, and a safer working environment would be created free from odors and dust particles typically generated by fossil fuels—all while reducing energy consumption.[11]

CONCLUSIONS

Even though the introduction of green engineering concepts into a design course was initially met with disapproval from students, by the end of a 14-week semester they found the greened heat transfer problems "useful" and "enlightening." More importantly, students found that the greened heat transfer problems increased their awareness and interest in the field of green engineering. Overall, the later problems, which were more practical in nature, fared much better with the students than the early problems that were more introductory and general in nature. A mid-semester assessment of the course modified the dissemination of the greened problems to the students.

The primary textbook used for the course was by Kern and the design portion of the greened problems did not always correspond well to the class material.[12] Instead, students were given the solutions to the design portions of each greened problem and were expected to concentrate on only the parts that related to green engineering concepts. This worked quite well. Homework grades increased and the students indicated that they began to enjoy working on the problems when the frustration associated with the design elements was eliminated.

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Biochemical Engineering

Continued from page 215

bacterial or mammalian cell cultures, from extraction of a natural source, or from chemical synthesis?

- ► *List two products in the pipeline. What stage are these drugs at, i.e. Phase I, II, or III clinical trials, or approved by the FDA for production? What is each product used for? How does each product work? What type of drug is it? How is it made?*

This project is assigned on the first day of class to help students initiate their job search. It is due after the lecture on the drug-discovery-to-manufacturing process, in which specific examples are presented. The project comprises 10 percent of the course grade and is graded based on the quality and completeness of the answers to the above questions; for instance, do the answers demonstrate an understanding of the mechanism of the drugs' actions?

CONCLUSION

The following are student comments from teaching evaluation forms of this course:

- *Gave us an understanding of how every lecture would be used and how it fits in with the rest of the quarter.*
- *Activities in the course encouraged the student to learn and apply the material.*
- *Made the class fun and informative.*
- *Outside assignments were relevant and took a reasonable amount of time to finish.*
- *The material was an excellent overview of what is needed to work in biotech.*
- *I really strongly consider this as a potential career field.*

Through this course, students see the connection of each lecture to the drug-discovery-to-manufacturing process. In-class activities such as those presented in this paper were effective in communicating biological fundamentals and their implications. In addition, students were engaged in two projects designed to

- *Explore the societal and ethical issues involved in the application of biotechnology*
- *Explore the scientific and business aspects of the biotechnology and pharmaceutical industry*

The course covered the basics required for working in the area of cell-culture process development in an interesting and fun way without overburdening last-semester seniors.

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A Successful "INTRODUCTION TO ChE" FIRST-SEMESTER COURSE

Focusing on Connection, Communication, and Preparation

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As a new assistant professor at the University of Massachusetts Amherst (UMass), my first teaching assignment was "Introduction to Chemical Engineering." Being a new faculty member, I had my preference of courses to teach, and after some serious consideration I chose the first-semester engineering students. In my six years at UMass I have been fortunate to have taught this course four times now, and as a result I have learned a great deal about how to effectively teach and motivate beginning engineering students. The course is primarily designed for first-semester engineering students who have a strong interest in pursuing chemical engineering as a major, but it is also attended by transfer students and upper-class, novice engineering students (*i.e.*, transfers from chemistry or biochemistry).

Many chemical engineering departments offer freshmen-level introductions to engineering courses, but few focus solely on chemical engineering,[1] and even fewer focus on first-semester freshmen. The format and content of these offerings are varied and include such things as general engineering education,[2-3] faculty/advisor seminars,[4-5] and laboratory experimentation.[6-7] This paper describes the design and implementation of a first-semester freshmen chemical engineering course.

FIRST YEAR ENGINEERING AT UMASS

The UMass College of Engineering has instituted a two-course sequence in each respective department to teach beginning engineering students the fundamentals of engineering. Each two-course sequence has been designed to provide new students with an excellent foundation in a specific engineering discipline (*i.e.*, chemical engineering, civil and environmental engineering, mechanical and industrial engineering, and electrical and computer engineering). There is flexibility, however, so students can switch mid-sequence if they decide to pursue a different discipline at the completion of the first-semester course.

This two-course sequence, which has evolved over the years with significant input from both students and faculty, incorporates discipline-specific activities. The two-course sequence in chemical engineering consists of a first course that is further described in this paper and a second course that extensively covers material balances and phase equilibria. The combination of these two courses provides students with an extraordinary background in chemical engineering fundamentals in addition to giving them a broad perspective of what the field of chemical engineering offers. Some students who transfer to UMass or who decide to switch to chemical engineering from another discipline in the spring semester enroll in the second course without taking the first course. In the main, these students fare well since the fundamental material balance content is repeated in the second course. Students can enroll in the first course the following year to gain experience in design, economics, and communication.

COURSE OBJECTIVES AND DESCRIPTION

In addition to introducing the students to the basic prin-

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TABLE 1
Course Syllabus

Week	Topics during "lecture" (2 x 1.25 hours) and "laboratory" (50 minutes) periods
1	Course introduction; Computer set-up, printing, and establishment of accounts
2	Physical sciences library introduction; Introduction to the Internet and Microsoft Word*; Units, conversions, and engineering estimation
3	Introduction to Microsoft Excel**; Effective technical writing; Introduction to processes (unit operations, flowsheets, etc.)
4	Ammonia synthesis—process design improvements; Material balances on nonreactive processes
5	Material balances—in-class exercises; Process economics
6	Process economics (continued); Learning in teams—discussion of the group project; Peer review of paper
7	Process economics game; Leblanc process—an illustration of chemical engineering principles[11]; Tour of the unit operations laboratory*
8	UMass Chemical Engineering faculty research panel; Examination review; Midterm examination
9	Introduction to Microsoft PowerPoint; Presentation skills workshop
10	Student midterm presentations**; Industry career panel
11	Introduction to Mathcad**
12	Safety in the laboratory and plant—case studies
13	Engineering scale-up
14	Energy balances
15	Student final presentations**; Engineering ethics; Course summary

* *Indicates activities held during laboratory periods; laboratory periods include computer instruction, departmental tours, presentations, and communication skills workshops*
** *Indicates activities held during both lecture and laboratory periods*

TABLE 2
ABET-Type Outcomes

At the end of this course students should...

- Understand what chemical engineering is and what careers are possible with a degree in chemical engineering
- Be able to use Microsoft Office (Word, Excel, and PowerPoint) to write technical papers, create spreadsheets to perform calculations, and design effective presentations
- Develop proficient oral presentation skills through group project presentations
- Understand the role of chemical engineers in process design
- Understand the importance of process economics in process design
- Be able to perform material balances on nonreactive systems
- Acquire an appreciation for the role of ethics and laboratory safety in the field of chemical engineering
- Be prepared to use the principles and tools learned in this class to solve problems not covered in detail as part of this course and to continue learning related material as needed in the future

ciples of chemical engineering (*e.g.*, mass balances, process design, engineering economics, scale-up, etc.), the objectives for the course are essentially threefold: first, to educate students about the variety of possible careers one can pursue with a degree in chemical engineering so that they can confidently decide if this degree is, in fact, what they ultimately desire; second, to create an environment where students can develop effective oral and written communication skills through individual writing assignments, group work, and classroom presentations; and third, to foster a learning atmosphere where students can openly discuss relevant issues (*e.g.*, engineering ethics) and become "connected," *i.e.,* familiar, with one another and with the faculty in the department. Table 1 is an abbreviated course syllabus, which outlines the activities planned for the semester. Throughout this paper, the implementation of specific activities for attaining these classroom goals is discussed. A list of ABET-type outcomes is additionally presented in Table 2.

CHEMICAL ENGINEERING AS A CAREER CHOICE

It is my opinion that most students in the introductory course chose chemical engineering as a potential major based on the simple fact that they enjoyed chemistry and mathematics in high school, but when queried as to what types of jobs they would pursue with this degree, most were unable to answer. Therefore, throughout the semester, activities are planned to introduce them to the types of careers that are available with a chemical engineering degree (they are usually very surprised to discover the choices!).

A portion of the first day is spent showing a video titled "Careers for Chemical Engineers," which is available through AIChE. This medium is an excellent introduction to the numerous arenas in which chemical engineers can focus their careers upon graduation. Additionally, the video is an effective way of illustrating the types of skills that students should develop during their academic careers, including computational, communication-related, and problem solving (all of which are important, regardless of what they ultimately choose as a career!). An "industry career panel" is planned, with chemical engineering representatives (typically UMass alumni) from different industries (*e.g.*, chemical, microelectronics, pulp and paper, biotechnology, etc.). This panel format has proven to be an extremely successful tool for addressing the career-education objective and for motivating the students to seek additional information. I also discuss the types of research that I personally do and incorporate some of my own results into problem sets, thereby allowing the students to see how chemical engineering fundamentals can be applied to solving nontraditional problems (*e.g.*, biotechnological problems). The students are encouraged to become involved in the local AIChE student chapter as freshmen, which also affords them access not only to the invited speakers (*e.g.*, career office personnel, industry representatives, etc.) but also to the upper-class chemical engineering students, whose own objectives are more well-formed.

A Web site has been developed for the first year (<http://www.ecs.umass.edu/che/che110/index.html>) that includes not only details on the two first-year courses offered by the department, but also has information on chemical engineering as a career choice, career skills, scholarships and internships, and safety and ethics. Students are strongly encouraged to partake in summer industrial internships or research opportunities as early as the summer following their first year. Opportunities regarding research experiences for undergraduate programs are summarized on the Web site and brought to the students' attention throughout their first year.

Additionally, many of our students are in the Honors Program (Commonwealth College) and are required to complete a senior honors research thesis. Students are therefore encouraged to learn about departmental research as freshmen, so they can begin research in either their sophomore or junior year (when Honors Research Fellowships are available). Many of our students have been amazingly productive, with published articles resulting from their research work.[8-10] When beginning students learn of the achievements of upper-class students and alumni, they become excited about the opportunities available to them.

PREPARATION

The UMass chemical engineering curriculum has moved the traditional mass-and-energy balances class (typically a fall-semester, sophomore-level course) to the second-semester freshman year. Therefore, even though the "Introduction to Chemical Engineering" class is not a requirement for graduation, there exists a need to begin exposing students to "real" chemical engineering calculations early in their education. Additionally, students should be introduced to the type of work a typical chemical engineering class entails (calculations, calculations, calculations!). Thus, although the class focus is (in part) on connection and communication, suitable time is also dedicated to learning some basic chemical engineering fundamentals. The concept of process design and optimization, which separates chemical engineering from the other engineering disciplines, is very well explained in a book written by Duncan and Reimer (*Chemical Engineering Design and Analysis, An Introduction*, Cambridge). In this reading, examples are used to illustrate the building and improvement of processes based on physical or chemical changes. The LeBlanc Soda Process is used as an example to depict all aspects of design from improvements in technology to attention to safety and the environment.[11] Students are also taught engineering economics (an economics game was developed where groups of students compete to design the most cost-effective process), nonreactive material balances, and scale-up issues. Freshman engineering design experiences give students exposure to the creative nature of engineering; there has been a recent resurgence in freshman-level design activities.[12]

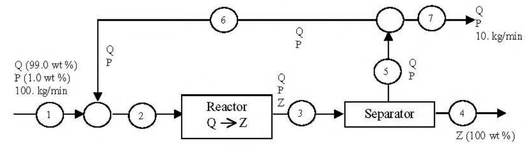
Students learn to effectively write nonreactive material balances on simple systems (see Table 3 for some specific examples of both homework and exam problems). Calculus is not needed for students to understand the concept of a material balance, and the inclusion of this material in the first-

TABLE 3
Examples of Material Balance Problems

Appeared on a Midterm Exam
A liquid mixture containing 30 mol% benzene (B), 25 mol% toluene (T), and 45 mol% xylene (X) is fed at a rate of 1275 kmol/h to a distillation unit consisting of two columns. The bottoms product from the first column is to contain 99 mol% X and no B, and 98% of the X in the feed is to be recovered in this stream. The overhead product from the first column is fed to a second column. The overhead product from the second column contains 99 mol% B and no X. The B recovered in this stream represents 96% of the B in the feed to the second column.
(A) Draw and label a flowsheet for this process.
*(B) Calculate the molar flow rates (kmol/h) and component mole fractions for the product streams of the second distillation column.**

Appeared on a Homework Assignment
Ethanol can be synthesized by yeast from grain and water in a reactor. Assuming an idealistic process, the yeast converts 2 kg of grain into 1 kg of ethanol and 1 kg of water. A perfectly efficient yeast reactor (efficiency = 1.00) would convert all of the grain entering the reactor. A reactor with an efficiency = 0.50 would convert half the grain entering the reactor, and so on. The feed is 100 kg/min, 20 wt% grain, and 80 wt% water.
(A) Calculate the total flowrate of the reactor effluent for an efficiency of 0.50. Also calculate the flowrates of all components in both the reactor feed and reactor effluent streams.
*(B) Calculate the reactor effluent composition using a range of reactor efficiencies starting at 0.00 and increasing in step by 0.05 up to 1.00. Also, create a chart that will display the effluent grain flowrate as a function of reactor efficiency. Explain the significance of your results.***

Appeared on a Homework Assignment
The chemical Q reacts to form Z. Unreacted Q is separated from Z and recycled to the reactor. The feed contains an impurity, P, which is inert and is purged from the system via stream 7. The splitter purges 5.0% of stream 5. Note that a mass balance on Q must account for the Q that reacts to form Z. Likewise a mass balance on Z must account for the Z formed from Q.
(A) Which stream has the highest flowrate of Q?
(B) Calculate the flowrate of product stream 4, in kg/min.
(C) Calculate the composition of purge stream 7.
*(D) Calculate the flowrate and composition of stream 2.***



* *Adapted from Felder, R., and R. Rousseau,* Elementary Principles of Chemical Processes, *3rd ed., John Wiley & Sons, New York, NY (1999)*
** *Adapted from Duncan, T., and J. Reimer,* Chemical Engineering Design and Analysis: An Introduction, *Cambridge University Press, New York, NY (1998)*

semester course gives students a realistic view of the types of approaches chemical engineers use to solve problems. I have found that students thoroughly enjoy this section of the course (although most feel quite challenged) and they gain confidence in their ability to pursue chemical engineering as a major. Students are also well prepared for the second-semester "Fundamentals of Chemical Engineering" course that is dedicated to mass balances and phase equilibria.

Good portions of the class and homework assignments are dedicated to developing students' computational skills, in particular the use of Microsoft Office (Word, Excel, and PowerPoint) and Mathcad. This is particularly important because there is always a certain percentage of students who have reached this level of their education with very limited computer skills. Since these computer applications will be used in all future chemical engineering classes, it is critical that the students know how to maximize their use. To achieve this end, there is a mandated requirement that all homework assignments must be completed on the computer (thus assuring that the students are getting the practice they need).

Since there is no formal requirement at UMass that students take a course in engineering safety or engineering ethics, two class periods are spent discussing safety in the laboratory and plant and engineering ethics. A case-study approach is used to stimulate thought and discussion about the importance of these subjects in the chemical engineering profession. Although only a short time is spent in the classroom on these subjects, the students are encouraged to incorporate ethics and safety into their homework problems as well as into their group project assignments.

CONNECTION

The majority of students enrolled in the "Introduction to Chemical Engineering" class are first-semester freshmen. Most of them have recently arrived on campus and are new to the college experience itself. UMass has approximately 25,000 students, and most of the first-year classes are conducted in large lecture halls, giving the students limited contact time with the faculty and upper-class students. Studies have demonstrated the importance of students feeling "connected" with the university in terms of student success, happiness, and retention. Previous studies have demonstrated that advising and mentoring during the freshmen year were successful in decreasing attrition rates for engineering students.[13]

Because this introductory course is relatively small (40-50 students) in relation to the other first-year courses, the opportunity exists to foster "connections." Although this takes a bit of time on the instructor's part, it is well worth the effort in terms of yield in student retention and class performance. Getting to know each student on a first-name basis is critical and being easily accessible to students is a must. Other means of fostering this "connection" are

(1) *A class lecture that is dedicated to a "faculty research panel" where several faculty in the chemical engineering department take part in a panel presentation and discussion about their research activities. Students get to know the other faculty in the department, develop enthusiasm about the ongoing research programs, and begin to see the diversity in the chemical engineering discipline.*

(2) *An outside-class activity (which most students attend) that is arranged where the sophomore and freshmen classes are brought together in a casual environment to discuss issues relating to the UMass Department of Chemical Engineering and curriculum.*

(3) *A unit operations laboratory tour, given by the senior class. The tour takes place in the same time slot as the senior laboratory so that all the seniors are present and the equipment is operational. This not only allows beginning students to see what types of experiences are ahead of them, but also gives them the time to ask questions of the seniors.*

(4) *An "industry career panel," comprised of alumni, that not only gives the students the opportunity to see firsthand what types of jobs are available with their chemical engineering degree, but also allows them the chance to "connect" with former students and recent graduates.*

(5) *All students are encouraged to get involved with the student chapter of AIChE. The upper-class students are enthusiastic about including beginning students in their activities and the students feel as though they have a home in the department.*

COMMUNICATION

Group Projects for Collaborative Learning

Throughout the semester, students learn about process design, flowsheet construction, material and energy balances, engineering economics, laboratory safety, and ethics (see Table 1). With this background to support them, the students are assigned to groups of three and are given a particular chemical or pharmaceutical to research throughout the semester (*e.g.*, ethanol, penicillin, MTBE, sulfuric acid, ethylene, etc.). They are responsible for investigating the history of the process(es) involved, for describing the current process methods including the construction of flowsheets (synthesizing all information in the literature), for creating a simple market report, for performing an economic analysis, and for identifying potential problems in the process associated with hazardous materials, waste, inefficiency, and safety. The groups must give two presentations during the semester and then write a final report, which serves to hone both oral and written communication skills. For the second presentation students are asked to redesign the process based on their analysis of efficiency and minimization of waste. All students must partake in both presentations.

A presentation skills "workshop" has been added to the syllabus to provide students with appropriate background on how to give an effective presentation. This "workshop" is cofacilitated with experienced university personnel. As part of the group project, students are required to complete a group-member evaluation form where they evaluate themselves and all group members (on a scale of 1 to 5).[14] The evaluation criteria include reliability, research, analysis, oral presentation, report writing, and leadership. The use of an evaluation system holds the students accountable and helps bring about conflict resolution, which creates a more realistic team environment. Also, using an evaluation form at the midterm point in the project allows the instructor to foresee problems with certain groups that can possibly be solved before the semester is finished. Currently, peer evaluation is used by the instructor solely to gauge group performance, but there are plans to include student review of feedback and team conferences to discuss group dynamics in future course offerings. Students embrace this project and are amazingly successful in generating a reasonable flowsheet and identifying process inefficiencies. This project is extremely effective at teaching students the concept of process design, which most chemical engineering students do not begin to understand until much later in the curriculum.

Emphasis on Written Communication

Although the group project and presentations are successful at enhancing students' communication skills, the individual-paper assignment helps them develop technical-writing skills. The students are responsible for writing a research paper on the past, current, or future impact of chemical engineering on society and are required to reference a minimum of five sources, only one of which can be from the Internet. I learned early on that students rely too much on Internet material, which may or may not have been peer-reviewed or regulated. At the beginning of the semester, one of the head librarians from the Physical Sciences Library visits the class and gives a complete introduction to library sources, including a list of relevant chemical engineering publications (*e.g.*, books, reference materials, journals, newspapers, etc.).

When this assignment was first implemented, the quality of the papers received was questionable in terms of organization, research, writing skills—and the simple ability to follow directions! This problem was somewhat solved through the institution of a technical-writing workshop, increased instruction on researching technical subjects, and the addition of a peer-editing session a week before the deadline. The technical writing workshop is facilitated by the course instructor and involves reviewing a publication on technical writing[15] and critiquing previous years' writing submissions.

For the in-class peer-review session, students are anonymously assigned two papers to review and are instructed on how to effectively critique and provide feedback. They edit the papers and provide comments directly on the manuscript. Authors then receive the written feedback and incorporate changes into a revised submission. The result is that most students dramatically improve their technical-writing skills; this was assessed through qualitative analysis from several years of teaching this course.

TABLE 4
"Pitfalls" Handout for Technical Writing

- Follow directions!!! Many students do not follow the formatting directions (paper length, reference and citation format, margins, title page, etc.) or the content instructions, and therefore lose significant points on the final paper grade.
- Include citations in the text of your paper. Citations provide the reader with the sources of information you have used to support your ideas and conclusions. Without citations, your paper will lack credibility.
- Perform a simple spell check on your paper to catch spelling and grammatical errors.
- Read over your paper before you hand it in. Many problems with punctuation, run-on sentences, and incomplete sentences can be avoided if you read the text out loud to yourself. Some misused words will not appear on a spell checker. For instance, the error in the sentence "Chemical engineering if fun," will not be detected using a spell checker.
- Pay attention to sentence structure and grammatical format. Some common mistakes are listed below:
  - There should be two spaces after a period (as well as after a question mark and exclamation point) before beginning a new sentence.
  - Only proper names and nouns should be capitalized. For example, many capitalize words like Chemical Engineer, which should be in lowercase. However, the University of Massachusetts Department of Chemical Engineering should be capitalized.
  - Citations in the text should be placed before punctuation (e.g., period, comma, etc.).
  - Acronyms should be written out in full the first time they appear in the text.
  - Author lists should not be shortened to et al. in reference lists, only in the citations.
  - Try not to use the words it, this, that, etc., as nouns. More descriptive words will make your sentences clearer.
  - Avoid using the first person when writing scientific or engineering papers.
  - Do not write extraneous commentary in the text.
  - Be careful when placing commas—the meaning of a sentence can be changed.
- Write about subjects that you understand. Don't bite off more than you can chew!
- Avoid excessive and improper use of quotations in scientific and engineering papers. Quotes taken directly from sources should add significant meaning to the paper or else you should paraphrase and cite the information. For instance, facts and statistics should not be quoted.

TABLE 5
Examples of Student Research Paper Titles

- Development of Orthopedic Limbs
- Contribution of Chemical Engineering to Research on Alzheimer's Disease
- The Process of Manufacturing Urethane Wheels for Roller Sports
- The Removal of Chlorine from Water
- Producing Scents: The Production of Perfume and Cologne from Past to Present
- The Breakdown and Disposal of Nerve Gas
- Design of Artificial Kidneys
- Wastewater Treatment
- The Process for Decaffeinating Coffee
- The Synthesis of Tennis Balls
- Development of Mammalian Cell Processes for Supply of Pharmaceuticals

It must be remembered that most beginning engineering students have never written a technical research paper—the majority of their writing experiences have thus far been nontechnical, *i.e.*, high-school English and history. A "pitfalls" handout was developed that highlights problems observed with past classes. Some examples include avoiding excessive and improper use of quotations and including citations in the text to provide the reader with the sources of information used to support ideas and conclusions (see Table 4). Students are also provided with a list of previous students' paper titles (see Table 5 for some creative examples). Students are advised to choose a subject that interests them and to avoid complex material for which they have no or limited background. Although many faculty are starting to mandate oral presentations from students, most faculty still do not address the need to develop effective written communication skills. Further development of this course will include incorporation of additional writing assignments.

ASSESSMENT

At the end of the course, students are asked to evaluate their learning in several categories that reflect the course objectives. Responses to student surveys conducted during the past three years (with two separate instructors) are shown in Figure 1. Responses were consistently high, even with a turnover of instructors. Virtually all students agreed that the course was successful at illustrating the field of chemical engineering and the potential careers possible with a degree in chemical engineering. Additionally students felt they gained critical knowledge in chemical engineering fundamentals as well as proficiency in communication. The overall course evaluations were very high (> 4.0), when students were asked to compare this course to others offered at UMass. Qualitative feedback has also been extremely positive, particularly from minority and female students. Collectively, these data indicate that the course was successful in meeting the educational objectives. Before the redesign of this first-semester course, it was consistently rated one of the worst in the department; today, it is one of the most highly rated. Additionally I have appreciated the opportunity to get to know the beginning students early in their academic careers and to assist in connecting students with other departmental faculty.

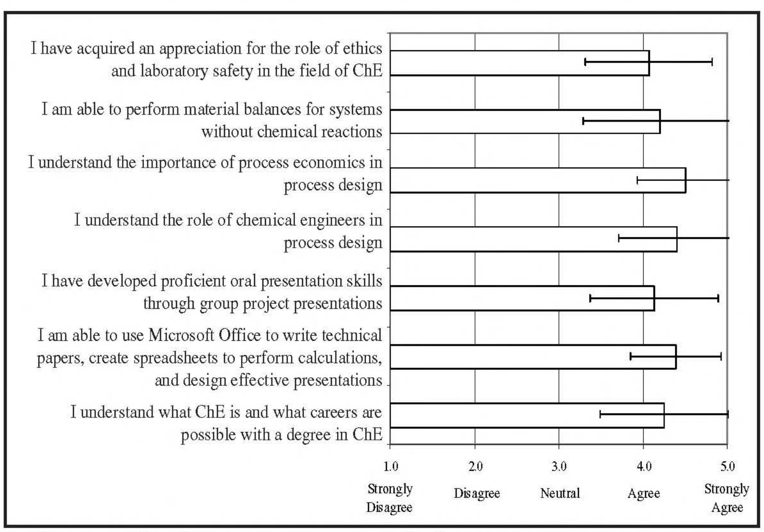


Figure 1. *Student responses to end-of-course assessment survey.*

SUMMARY

Do not underestimate the ability of beginning engineering students to learn! This course, although the workload is significant, is always highly evaluated and described as "useful" in student development. The overall time commitment can be managed through the use of teaching assistants, but faculty instructors must make the effort to get to know the students to foster their connection with the department. The right combination of preparation, connection, and communication through the described activities is instrumental in developing and preparing successful and enthusiastic chemical engineering majors.

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SURVIVOR: CLASSROOM

A Method of Active Learning that Addresses Four Types of Student Motivation

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Phil Wankat[1] succinctly states the importance of active learning in the classroom as "Involved students learn!" As a result of the dissemination of overwhelming evidence supporting active learning, more engineering faculty (including, presumably, almost all of those who would choose to read this paper) are using active learning in their classrooms.[2-4] A survey conducted by Brawner, *et al.*,[5] indicated that 60 percent of responding engineering professors used some active learning. While the benefits of active learning are clear, simply breaking students into small groups to work on problems during class does not automatically address the pervading issue of student motivation. Biggs and Moore[6] classify four primary types of motivation:

- **Intrinsic** — *learning because of natural curiosity or interest in the activity itself*
- **Social** — *learning to please the professor or your peers*
- **Achievement** — *learning to enhance your position relative to others*
- **Instrumental** — *learning to gain rewards beyond the activity itself (better grades, increased likelihood of getting a high-paying job, etc.)*

As such, an active-learning activity that addresses all four of these motivational categories would be useful. Unfortunately, professors tend to assume that things that would motivate them will also motivate their students. The problem is analogous to issues with learning styles in engineering education: Professors tend to teach the way *they* prefer to learn, which negatively impacts the learning of students with different preferences.[7-9] Not all students are inherently thrilled with solving energy balances, even when working in groups with their peers.

Of course, motivation is a far more complex series of cognitive processes than can be completely addressed with a single activity. Bandura[10] emphasizes the motivational importance of self-efficacy—the belief that "one can bring about positive results through one's own actions[11]"—by stating that self-efficacy impacts how much effort people offer and how long they will persevere when faced with obstacles. Ponton, *et al.*, [12] argue that it is paramount for a professor to incorporate strategies that enhance efficacy. Therefore, all students who participate in the learning activity must practice relevant exercises that develop both their skills and their confidence in their own abilities.

Ten years ago when I was teaching my first class, the sophomore-level materials and energy balances course, I was fortunate enough to have dinner with Rich Felder one evening and to talk about pedagogy and learning styles. The next day, I broke my class into small groups and in-

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stead of my lecturing to them about the problem, they solved it themselves. I was happier. Most of the students were happier. And they seemed to be learning more, but too many of them never really engaged in the activity. Assigning roles for team members helped, but it did not fix the problem. The student evaluations were very positive, but the students who did not engage during the active learning exercises were disproportionately represented in the group that did not make it to their junior year. The challenge was to find an activity that would motivate a wider range of students so the entire class would engage actively in the group problem solving. The pedagogical literature[13-15] shows that student involvement has a significant impact on student success and satisfaction.

The challenge was to find an activity that would motivate a wider range of students so the entire class would engage actively in the group problem solving.

Wankat and Oreovicz[16] proposed using quiz games modeled after popular formats such as *Jeopardy* or Trivial Pursuit as an active-learning alternative to lecture, but these games lend themselves better to knowledge-based questions than to problem solving. I have used the *Hollywood Squares* format in a materials science class for such questions, but it did not seem appropriate for a materials and energy balances class. Susan and James Fenton[18] at the University of Connecticut developed a very effective game called "Green Square Manufacturing" that came closer to meeting the needs of the class, but it did not necessarily address all four motivational factors, nor did it have the pop culture tie-in that I wanted. Finally, the idea of adapting a version of the CBS "reality" game show *Survivor* came to me. With inspiration and a little preparation, a game that met my needs was developed.

THE GAME

Students in the materials and energy balances class are broken into "tribes" of seven to eight people. At Rowan, this usually results in three tribes, but the number of tribes does not substantially alter the flow of the game. The tribes sit together much as they would in any group problem-solving exercise. If inadequate space is available, the tribes may self-segregate into smaller subgroups. Each tribe names itself.

The team members are permitted to have their textbook, notes, a calculator, and pencil and paper with them, but the book and notes must be closed at the beginning. I write a problem on the board, but they must not look up any values or begin writing until I say to begin.

Once they begin solving, the first tribe that has an answer to the problem has a member raise a hand. The other teams stop and the first team reveals its answer. If it is correct, that tribe has immunity and it does not lose a member. If the answer is wrong, the tribe cannot win immunity and the remaining tribes continue with the problem until one tribe successfully solves the problem or all but one tribe has provided an incorrect answer. To avoid issues of round-off or interpolation, I accept any answer within five percent of my answer. A representative from the successful tribe goes to the board to present the solution to the problem, so that the rest of the teams can consider their solution strategies.

At the end of the first problem, one tribe has earned immunity and every other tribe must lose one member. The method for elimination that seems to work best is

- In the first round, tribe members vote off a member of their own tribe
- In the second round, the tribe with immunity votes off a member of each of the other tribes
- In the third round, one member of each tribe is randomly eliminated by drawing a name

If there are more than three rounds, the steps are repeated in order. In the television show, the tribe members always vote off a person of their own tribe, but initially I was reluctant to allow voting at all. I worried that feelings would get hurt, self-efficacy would be damaged, and the students who most needed the reinforced problem solving would be eliminated the quickest. The students, however, were unambiguous: They wanted to vote.

As it turns out, the alternating system described above cures many woes. In almost every tribe, there is one player who wants to leave the game (for a variety of reasons). This person is almost always voted off first. Absent students are also assigned to a tribe and they are also quickly voted off. When the victorious tribe votes a member off of another tribe, they uniformly take out the strongest students. The random round is, of course, random. Ultimately, the average students who have enough skills to solve the

As the game progresses, the students gain confidence in their ability to write and solve problems. The strong students who are eliminated in the second round recognize why they were eliminated and help the weaker students with aspects of the newly created problems.

problems, but who genuinely benefit from reinforcing the concepts, survive the longest.

Students who have been eliminated in any round are given the task of designing and solving a problem to be used in later rounds. Thus, while they are no longer participating in the main activity, they remain actively engaged in team-oriented problem solving. More importantly, they discover that they are not only capable of solving problems, but can also create new ones. These students spend much of the time reading the textbook (in many cases for the first time), looking for a problem idea. Because they must provide a solution as well, their problem-solving skills are also reinforced.

In a typical 75-minute class, there is enough time to get through about six rounds of the game. Speeding up the elimination process would allow for more rounds, but the students seem to thoroughly enjoy that aspect of the game and it provides adequate time for the eliminated students to develop their own problems. At the end of the first class, the tribes are dissolved, and all of the players who have not been eliminated become part of a single tribe.

The team dynamics are fascinating to watch. In some tribes, each member attempts the problem on his or her own, then the first one who finishes speaks for the team. In other tribes, the players assign roles. One or two people look up values from the tables while another sets up the problem. For less trivial problems, some teams take a few seconds to discuss solution strategies before diving in.

The second day of the game involves solving the problems as individuals, but otherwise the flow is the same. A problem is placed on the board, the first person who finishes it either receives immunity or fails to solve the problem, and the round continues. Players are eliminated by vote of the tribe in the first round, by choice of the player with immunity in the second, and by random draw in the third. The cycle repeats until a single player remains and is crowned as the grand champion. Groups of eliminated players develop and solve the problems used throughout this round.

The successful students are rewarded with bonus points on the 200-point final exam. Every player who survives to the second day gets three points, every original member of the champion's tribe gets two points, and the champion gets an additional five points. The bonuses are additive, so the champion will wind up with 10 points (five percent), while everyone else will get between zero and five points. In three years of playing the game, the bonus points have never altered the final course grade of the grand champion, but students battle ferociously for them all the same.

LINKS TO MOTIVATION AND SELF-EFFICACY

Intrinsically motivated students gladly participated in the activity because they liked the activity itself or were genuinely interested in solving new problems. The socially motivated students worked hard on the problems because they did not want to let their teammates or the professor down. Achievement-oriented students wanted to win because it was a contest, often independent of the reward or interest in the material. Finally, students with instrumental motivation tendencies wanted the bonus points in hopes of improving their final grade in the class.

In terms of self-efficacy, the weakest students are voted out in the first round, but soon find themselves successfully writing problems that will be used later in the game. As the game progresses, the students gain confidence in their ability to write and solve problems. The strong students who are eliminated in the second round recognize why they were eliminated and help the weaker students with aspects of the newly created problems.

STUDENT FEEDBACK

On the course evaluations at the end of each semester, the students were specifically asked the question, "Was *Survivor* helpful in developing an understanding of the subject matter?" On a five-point Likert scale with five representing extremely helpful and one representing not helpful, the mean responses to that question were 4.70 in 2001, 4.77 in 2002, and 4.80 in 2003. Specific student comments have included:

- *"The game made the course interesting."*
- *"Playing the game helped to stimulate thinking."*
- *"Game was fun for a change."*
- *"Creating our own problems was especially helpful."*

SUMMARY

The game show *Survivor* has been adapted and used for three years as a means of introducing active, team-oriented problem solving into a sophomore-level course on energy balances. The game provides incentive for students from all four motivational forms (intrinsic, social, achievement, and instrumental). By having students who have been eliminated continue to participate through developing new problems that are used in the game, the entire class remains engaged throughout the activity. Based on several key observations:

- *The students self-report that the game was beneficial and increased their motivation;*
- *The game was designed specifically to address different motivational styles;*
- *I (and other professors who have used the game) have directly observed that the level of participation increased in problem-solving activities;*
- *Performance of the students in subsequent thermodynamics classes improved after the game was introduced;*

I believe the game has provided an effective method of reinforcing problem-solving methodologies, as well as being extremely popular with students.

SAMPLE QUESTIONS

Used in *Survivor*-Model Active Learning Game

1. *One mole of a mixture containing 20% ethanol and 80% water at 20°C and one atmosphere is to be cooled to 4°C.*

   How much heat must be removed from the system?

2. *Given the following chemical reaction*

   Dahmene (g) + 20 IQ (g) $\rightarrow$ Newellium (g)

   What is the heat of combustion for gaseous Dahmene if the heats of combustion for Newellium and IQ are -4130 kj/mol and -246 kj/mol, respectively?

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PERFORMING PROCESS CONTROL EXPERIMENTS
Across the Atlantic

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Process control has increased in importance in the process industries over the past decades, driven by global competition, rapidly changing economic conditions, more stringent environmental and safety regulations, and the need for more flexible yet more complex processes to manufacture high-value products. Remotely controlled processes, which are increasingly being used in industry and research, allow a process to be analyzed and controlled—and data recorded and processed via a Web interface—without the need to be in the same physical location as the equipment itself.

Likewise, Internet-based experiments offer possibilities for students to use up-to-date technologies for remote operation and communication on a *real* system. Perhaps more importantly, they will give students essential training for what they're likely to encounter professionally.

The purpose of this paper is to report on the development, usage, and evaluation of a new exercise in process dynamics and control that incorporates a Web-based experiment physically located at MIT. We first describe the experimental equipment and interface used, then the new exercise, and finally the results of the student evaluation.

EXPERIMENTAL SETUP

The experimental equipment is a heat exchanger, set up for online use within the subjects of transport processes and process dynamics and control. This was done as part of the MIT iCampus project, where a number of Web-accessible experiments—iLabs—have been developed.[1] The experiment, contained in a laboratory in the Department of Chemical Engineering at MIT, has been used in the education of MIT chemical engineering students since November 2001. The equipment is manufactured by Armfield, Ltd. in Ringwood, England, and consists of a service unit (HT30XC) supplying hot and cold water, with a shell and tube heat exchanger (HT33) mounted on it. The service unit is connected to a computer through a universal serial bus (USB) port. The experimental setup is controlled and broadcast to the Internet by LabVIEW software from National Instruments (Austin, Texas). A Java-based chat capability is included, allowing communication during the experimental session among the students (who can collaborate online at different locations) as well as between the students and the tutor. The experiment

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can be accessed from any Internet-connected computer after registering and installing Java and LabVIEW plug-ins. For a detailed description of the hard- and software environment, refer to Colton, *et. al.*[2]

The experimental setup is shown in Figure 1; the heat exchanger is to the bottom right. The cold water flow, F_c, uses mains cold water from a tap in the laboratory and is controlled by a flow controller operating a valve. Temperature indicators measure the cold water inlet and outlet temperatures, T_{ci} and T_{co}. For the hot water flow, F_h, a pump controlled by a flow controller pumps water through a heated tank (to the top left) where a heater, controlled by a temperature controller, heats the water. Temperature indicators measure the hot water inlet and outlet temperatures, T_{hi} and T_{ho}. T_{hi} is also used as the input to the temperature controller. The heat exchanger was originally built to study the principles of heat transfer; its application was then broadened to study transient dynamics and control.

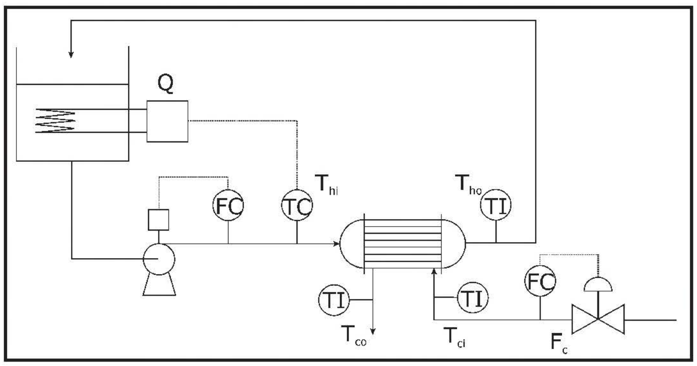

Figure 1. *Experimental setup (described in the text).*

In this initial collaboration, the focus has been on the controller for the hot water inlet temperature; the actual heat exchanger was only treated as a black box. The students' task was to achieve and maintain a desired water temperature into the heat exchanger, T_{hi}, under varying flow conditions.

CONTROLLER INTERFACE

The graphical user interface, shown in Figure 2, allows the user to change setpoint temperature, change hot and cold water flow rates, switch between co- and countercurrent flow patterns, and set the proportional (P), integral (I), and derivative (D) parameters. It also shows real-time values of temperatures, flowrates, and controller output. Temperatures and flowrates are also displayed in a scrolling graph and in tabular form, which is observed by clicking the "Data Table" tab, and the interface allows the user to record these data to a file for later retrieval. The charts can be rescaled by double clicking and entering new extreme values on an axis.

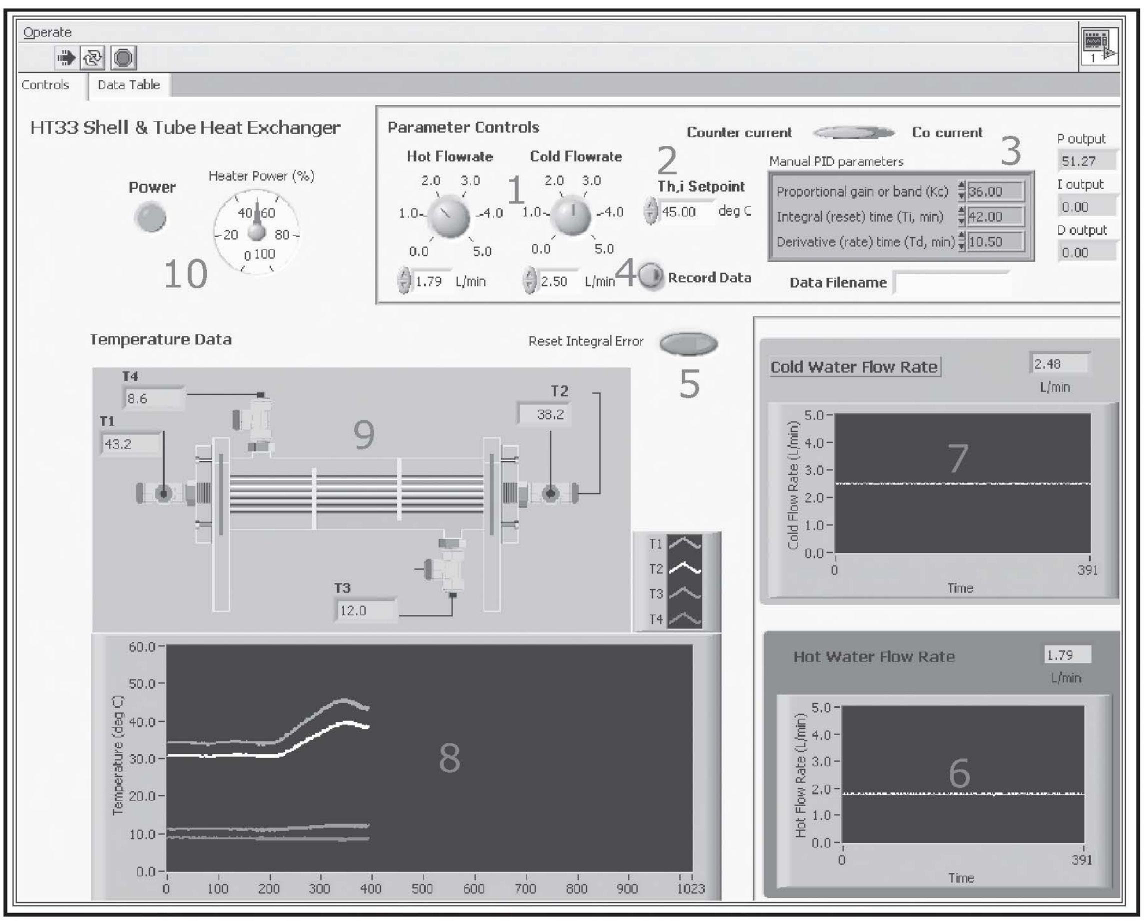

Figure 2. *The graphical user interface (numbers refer to text description).*

The desired values for (1) flowrates, (2) setpoint temperature, and (3) PID parameters are simply entered into the boxes. For the flowrates, there are also options to use the turning knobs or the arrow buttons. To save experimental data, which can later be retrieved from the Web site, a file name is entered and the "record data" button clicked (4). By entering appropriate values for the parameters, and using the "reset integral error" button (5) when necessary, students can run the experiment under P, PI, or PID control as required. The hot and cold water flowrates are shown in the two charts (6 and 7), with the instantaneous values in boxes. The inlet and outlet temperatures to/from the heat exchanger are shown in the chart (8) with instantaneous values in boxes in the schematic heat exchanger drawing (9). The dial (10) shows the heater output.

The interface looks and operates in exactly the same way if it is used to control an experimental setup next to the computer or if the setup is somewhere else. What the students do not see when performing the experiment over the Internet is the actual equipment. Maybe more importantly, they do not *hear* the noise of pumps and stirrers. To reduce this disadvantage, a Webcam has now been added to allow the students to see and hear the equipment when running the experiment.

Since we had the opportunity to use a real experiment we have not investigated the possibility of using a simulation. Simulations might be of good use when teaching control, but if students are to be trained for a real world with errors and irregularities, it is our view that a real system is preferable to a simulated one. This view is also supported by Ang and Braatz,[3] and Bencomo in his review of process control education.[4] From an interface point of view, running a simulation would not differ from running a real experiment, but the behavior of the system is likely to be more predictable.

On the same page as the interface is a Java chat facility (Figure 3) for communication among students and between the students and the tutor. A message is typed, and after the "send" button is clicked the message is visible to all users logged in to the chat facility.

THE EXERCISE

"Process Dynamics and Control[5]" is the title of a one-term course of 16 lectures taught in the second year of chemical engineering at the University of Cambridge. It aims to give students a variety of skills, such as how to write correctly formulated mass and energy balances and how to analyze and design controllers. Other institutions such as Rensselaer[6] and Illinois[3] have more lecture time to cover the topic and also have their students run a case study over several weeks[6] or spend several hours every week in the laboratory.[3] The course at the University of Cambridge is accompanied by an exercise that is an extended activity, undertaken individually, designed to test the students' knowledge of ideas covered in lectures. The exercise, although based on the course material, aims to challenge the students and extend their understanding. To practice presenting work clearly and concisely, each student writes a report on the exercise.

Unlike schools such as Utah[7] and Illinois,[3] the University of Cambridge has no huge experimental facilities to use for control experimentation. Further, space and time restrictions do not allow for a hands-on laboratory experiment to be added to the course. By incorporating the MIT iLabs heat exchanger operated over the Internet, the new exercise met course goals and gave Cambridge students the traditional benefits of a laboratory experiment. It also exposed them to remote-control software—much in line with the future predictions on remotely operated processes made by Skliar, *et. al.*,[7]

Figure 3. *The chat facility.*

and described by Bencomo.[4] The advantages of this exercise are therefore twofold: experiments can easily be performed on real systems (as opposed to simulations) where equipment would otherwise be unavailable, and students gain knowledge of remote-control software such as that used in research and industry.

The new exercise is divided into three parts.

- ▲ *A few preparatory questions on control, enabling the students to identify the relevant variables and to calculate control parameters from open-loop test data*
- ▲ *An experimental session with observations of a real system under P, PI, and PID control, followed by fine tuning of the control parameters and testing the response of the system to disturbances*
- ▲ *Processing of data obtained during the experimental session and follow-up questions penetrating deeper into the matter*

For the first part, students were given a piping and instrumentation diagram (see Figure 1) of the experimental setup and four sets of real data obtained from open-loop tests (*i.e.*, the reaction of the system to a step change in the process variable with the controller disconnected). From the piping and instrumentation diagram, the students were asked to identify: (a) the controlled variable, (b) the process variable, and (c) any disturbance variables. Most students identified the controlled and process variables correctly as T_{hi} and Q, respectively. The disturbance variables here are T_{ho} and F_h since this stream is what enters the heater bath, but T_{ho} is a function of F_c, F_h, T_{ci}, and T_{hi}, which complicates the matter. It also confused the students—thus illustrating the truism that real life is more interesting than idealized systems.

From the data supplied, the students were told to first identify which set was best suited to the desired operating conditions and then to apply the method of Cohen and Coon[8] to calculate an initial set of PID parameters to be used in the experimental session.

Cohen and Coon is one of the tuning methods covered in the lectures and is known to be nonrobust, but the method was deliberately chosen because we did not want the students to start their experiments with a perfect set of PID parameters. The main focus of the exercise is *not* choosing PID parameters from experimental data. Rather, the focus is the practical experiment itself, and during the experiment we wanted students to experience instabilities and have to further fine tune the system using their theoretical knowledge of control. Because the data were real and non-ideal, the resulting PID parameters could vary by at least a factor of three depending on how slope, final temperature, and dead time were interpreted from the data. Many students commented on this, and it was another useful experience with the difficulties that can arise when dealing with real data, as well as some shortcomings of the Cohen and Coon method.

After presenting reasonable estimates of the PID parameters to a tutor, each student was issued a username and password to log in to the experiment. During allocated time slots, students in groups of three or four logged in to the experiment at <http://heatex.mit.edu> using a LabVIEW interface. The Java chat facility was used for communication between the students and the tutor. After agreeing on initial PID parameters, the students' first task was to make qualitative observations of the system under P, PI, and PID control, noting phenomena such as offset and stability in the controlled variable. If the system did not stabilize, the students had to make changes to one or more of the parameters, using their theoretical knowledge of control—or trial and error—to obtain a stable system. Once happy with the steady-state behavior, the students tested their parameters by applying, and recording, the response to three step changes: (a) F_h step change of –1 L/min, (b) T_{hi} setpoint step change of +5 °C, and (c) F_c step change of +2 L/min. Some groups needed to further adjust their parameters to ensure the system was stable in response to the distur-

Since we had the opportunity to use a real experiment we have not investigated the possibility of using a simulation. Simulations might be of good use when teaching control, but if students are to be trained for a real world with errors and irregularities, it is our view that a real system is preferable to a simulated one.

bances. Most groups completed the experimental session within two hours, but some groups spent more time playing and testing responses to changes in the parameters, and spent up to three hours.

If the system did not stabilize, the students had to make changes to one or more of the parameters, using their theoretical knowledge of control—or trial and error—to obtain a stable system.

Following the experimental session, each student wrote an individual technical report, including his or her observations and changes to the parameters during the experiment. The reports showed that the students had gained understanding of the effects of the PID parameters on the controlled variable and how to adjust the parameters to mitigate for undesired effects such as slow or unstable responses under servo or regulator control. They also had to process their data by: choosing (and justifying the choice of) an error-response criterion, calculating its value for each disturbance, suggesting methods for further fine tuning, and discussing differences between the experimental system and an idealized stirred tank.

For the error-response criterion, some students chose the integral of the square error (emphasizing large errors) and others the integral of the absolute error (treating all errors equally). Both criteria were accepted as long as the choice was justified.

Because the students had just calculated the value of an error-response criterion, we expected a suggestion to minimize that for further fine tuning, but quite a few suggested other routes such as minimizing overshoot, rise time, or decay ratio. They also pointed out that different aspects are important to different systems.

Finally, students ranked the comparison to an idealized stirred tank as a useful exercise. They noted things such as the presence of dead times for the measurements in the real system, signal noise in the measured values for temperatures and flow rates, the real system being too complex to treat mathematically, and the mixing being nonperfect in the real system. Typically, students are used to doing this the other way around—by dealing with *idealized* systems and thinking about how a *real* system would behave.

EVALUATION

The equipment is designed to run over long periods of time with minimal maintenance, and once set up by the MIT staff it could be run for the complete course with only occasional supervision. Technically, the equipment and interface performed without fault for the duration of the course (ten three-hour sessions).

Student feedback was obtained by issuing questionnaires assessing the usability of the experiment and interface, the group work experience, the meeting of educational objectives, and the experience in comparison to exercises in other subjects. In the questionnaire, students had to state to what extent they agreed with a number of statements on a Likert scale ranging from 1, "I strongly disagree," to 7, "I strongly agree." A total of 36 students performed the exercise, and 23 of them handed in a completed questionnaire.

❑ ***Usability when Carrying Out the Experiment on the Web***
(Instructions, operation, time needed, and retrieval of data)

Students were provided with a Web-based exercise sheet and detailed instructions on how to carry out the experiment. Time spent with the experiment varied from 90 to 180 minutes. The students were satisfied with the instructions and managed well to use the LabVIEW interface and chat window, and to download their experimental data after the session. Easy comprehension and use of the interface and downloading of experimental data are listed by Bencomo[4] as some of the most important features of a remote experiment. Various suggestions for minor improvements of the interface were received.

❑ ***Working in a Group***
(Contribution to group and actual and preferred group size)

This exercise was one out of seven, with the others being performed individually. This one was performed in groups of four but the reports were written individually as usual. The

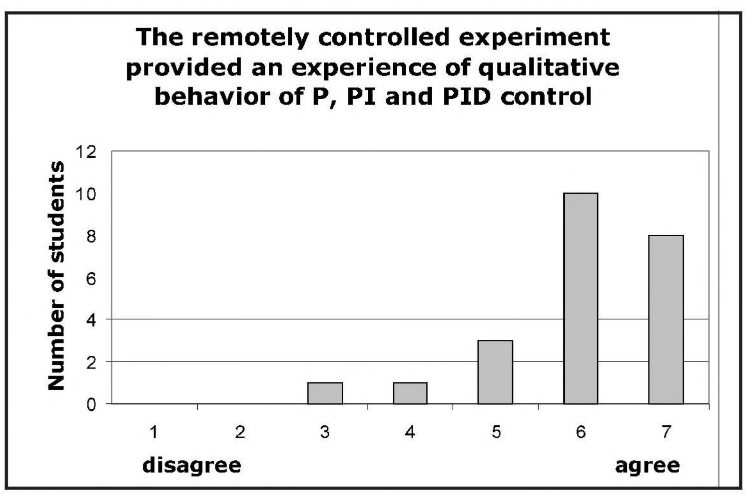

Figure 4. *Students ranked the remotely controlled experiment.*

students said they very much liked working in groups and felt they could contribute to the group. When it came to group size, the students' opinions fell into two categories—either seeing little or no reason to have smaller groups, or thinking that a smaller group would have been good. (Three students commented that three students would be the ideal group size.) From a teaching point of view, we would prefer smaller groups. This is a matter of resources available, however, since smaller groups require more experimental sessions and increase the associated workload for technicians and tutors. When this exercise was repeated during 2005, the group size was set to three students, which was also the group size used at Rensselaer.[6]

❑ ***Meeting Educational Objectives***
(Measurement and analysis of real data and qualitative behavior)

Even though some students commented on the lack of a sense of reality when performing the experiment, most agreed that it provided an experience of measurements and analysis of both real data *and* the qualitative behavior of P, PI, and PID control (see Figure 4). A Webcam, not yet in place at the time we used the experiment, has since been added to enhance the experience with video and sound from the laboratory equipment.

❑ ***Comparison to other exercises***

The other exercises were purely theoretical and performed individually. This exercise offered a change by being partly performed in a group and in providing a challenge to use theoretical knowledge to tune a real system. It was very positively received by most students (see Figure 5).

CONCLUSION

We have developed, used, and evaluated a new exercise in process dynamics and control incorporating a Web-based experiment physically located at MIT. We described the experimental equipment, the interface used, and the new exercise, and reported on student evaluation.

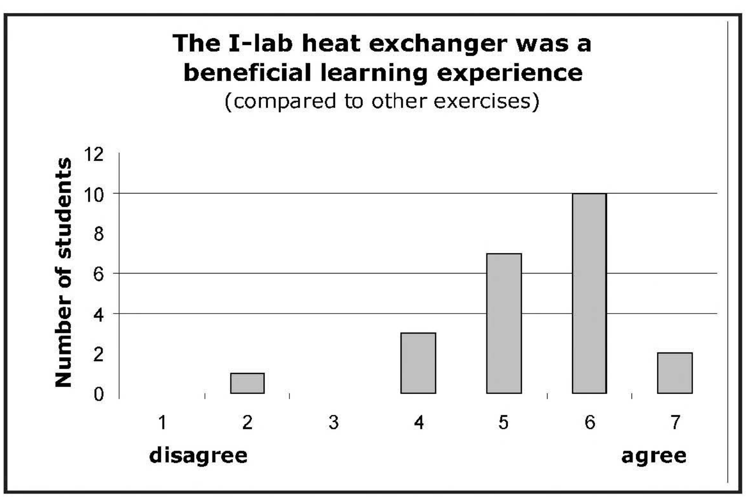

Figure 5. *Students ranked the remote-learning experience.*

The successful realization of this exercise shows that the technology is available and sufficiently stable to perform complex educational experiments over the Internet. The user-friendly graphical user interface and the interactive, fast-responding process were appreciated by the students, as shown by positive responses to the course-evaluation questionnaire.

The equipment is designed to run over long periods of time with minimal maintenance, and once set up by the MIT staff it could be run for the complete course with only occasional supervision.

The authors at the University of Cambridge are now in the process of developing assignments and hardware for a new experiment on chemical reactors for broadcasting to the Internet.

ACKNOWLEDGMENT

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A KINETICS EXPERIMENT

For the Unit Operations Laboratory

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The topic of kinetics, because it deals with change in molecular structure (as opposed to mere physical change), is, strictly speaking, not a subset of the term "unit operations." Nevertheless, many schools include a kinetics experiment in what is nominally called a unit operations laboratory (UOL) course. This paper describes a kinetics experiment that was recently added to the senior UOL course at Clemson. It deals with selection of the reaction, the design and operation of the apparatus, incorporation of appropriate safety equipment, and analysis of results.

Once the decision to add a kinetics/reactor design experiment had been made, the first issue to be resolved was whether or not to purchase a complete "off the shelf" experiment from a vendor (*e.g.,* Armfield or Hampden), or to design/build our own. The latter path was chosen for several reasons. One was that this strategy would provide an excellent learning opportunity for the group of undergraduate students who played a major role in the construction/debugging of the apparatus and in the determination of feasible operating conditions. This aspect will be described in a separate paper.[1]

Another reason for deciding to design our own experiment was that commercially available experiments use liquid-phase reactions (*e.g.,* saponification), whereas a heterogeneously catalyzed gas-phase reaction system was felt to offer several advantages, one of which would be greater variety regarding potential assignments since, with minor modification, the same apparatus could be used for many combinations of catalyst and reactants, often with major differences in apparent kinetics. Other advantages would be that such a system affords more accurate flowrate control/determination (through the use of mass-flow controllers) and more accurate composition measurements (through the use of a gas chromatograph equipped with a flame ionization detector). Furthermore, designing the experiments and conducting data analysis could be varied to fit the backgrounds of the students (and the temperament of the instructor). For example, the rate data could be fit to a simple "power law" expression or to a more complex Langmuir-Hinshelwood model that provides additional insight into what is actually occurring during the reaction process.[2] Finally, during the roughly eight months a year when the senior UOL course is not being taught, the apparatus would be available as a versatile platform for senior or graduate student research projects.

CHOICE OF REACTION/CATALYST

After considering several reactions, propane hydrogenolysis over an alumina-supported platinum (Pt/γ-Al_2O_3) catalyst was chosen for the experiment. Under the conditions used, the reaction can be considered effectively irreversible and ethane hydrogenolysis, a possible complicating secondary reaction, occurs to a negligible extent. Data analysis is also made easier by the small number of species involved and by the fact that the simple stoichiometry results in no change in the total number of moles (shown in Eq. 1).

$$C_3H_8 + H_2 \rightarrow C_2H_6 + CH_4 \tag{1}$$

In the experiment, the catalyst (in a sense) merely serves as a "means to an end," *i.e.,* students are not asked to study the catalyst *per se.* In designing the experiment, however, the choice of catalyst was important because the catalyst greatly influences the reaction rate, and thus, operational parameters such as reactor size, temperature, pressure, and flow-

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David R. Kuhnell and **Christopher I. McDonald** are recent chemical engineering graduates from Clemson University. As undergraduates, both were actively involved in oxidation catalysis research with Dr. Bruce and were the primary individuals contributing to the building/testing of the apparatus.

rate. An additional consideration was that the catalyst should experience minimal deactivation over the course of a given group's experiment (typically, three 3-hour periods) so that the determination of kinetic parameters would be straightforward. Combining both literature[3,4] information and our "in-house" experience[5,6] with this reaction over a variety of catalysts resulted in the selection of a commercial 0.6 wt.% Pt on γ-Al_2O_3 catalyst (PHF-5) obtained from Cyanamid.

EXPERIMENTAL APPARATUS

Figure 1 is a schematic showing the major features of the apparatus. The four main sections are

- *The reactor and furnace/temperature controller*
- *The feed gas system and flow controllers*
- *The combustible gas detector/alarm and emergency gas shut-off system*
- *The computer-controlled gas chromatograph*

The reactor consists of a 66-cm long stainless steel tube (15.9 mm OD, 13.6 mm ID) connected at each end to a Swagelok tee. Within the reactor, roughly 1.5 grams of 14 to 30 mesh (0.6 to 1.4 mm) catalyst particles are positioned at the midpoint, *i.e.,* roughly 30 cm from the inlet. The feed preheating zone between the reactor inlet and the catalyst bed is filled with 1.5-mm glass beads. These beads also serve, along with small pieces of Pyrex wool, to position the catalyst near the axial midpoint of the "wraparound" 1.3 kW Lindberg Blue M tube furnace. Due to low conversions and the small size of the catalyst bed, the catalyst temperature is approximately uniform and is measured using a 3.2 mm OD type-K thermocouple that is coaxial with the reactor and that has its tip positioned in the center of the catalyst bed. Readings from the reactor thermocouple are obtained using an Omega digital thermometer. Another type-K thermocouple is used to measure the furnace temperature, *i.e.,* in the region between the outside of the reactor and the inner surface of the furnace. This thermocouple is connected to a Barber-Colman temperature controller. In the reactor exit line there is a pressure gauge and a Tescom back-pressure regulator.

The feed-gas system consists of

- *Pressure regulators and high-pressure cylinders for the three gases used (instrument-grade propane, high-purity hydrogen, and high-purity helium)*
- *Normally closed solenoid valves for the hydrogen and propane lines that are energized (open) during normal operation and de-energized (closed) when the apparatus is not in use or when elevated levels of combustible gases are detected*
- *Three calibrated Brooks Model 5850E mass-flow controllers connected to a Brooks Model 0154 digital flow readout*

After being combined, the three streams may be either routed to the reactor inlet or to a bypass line (for feed composition determination).

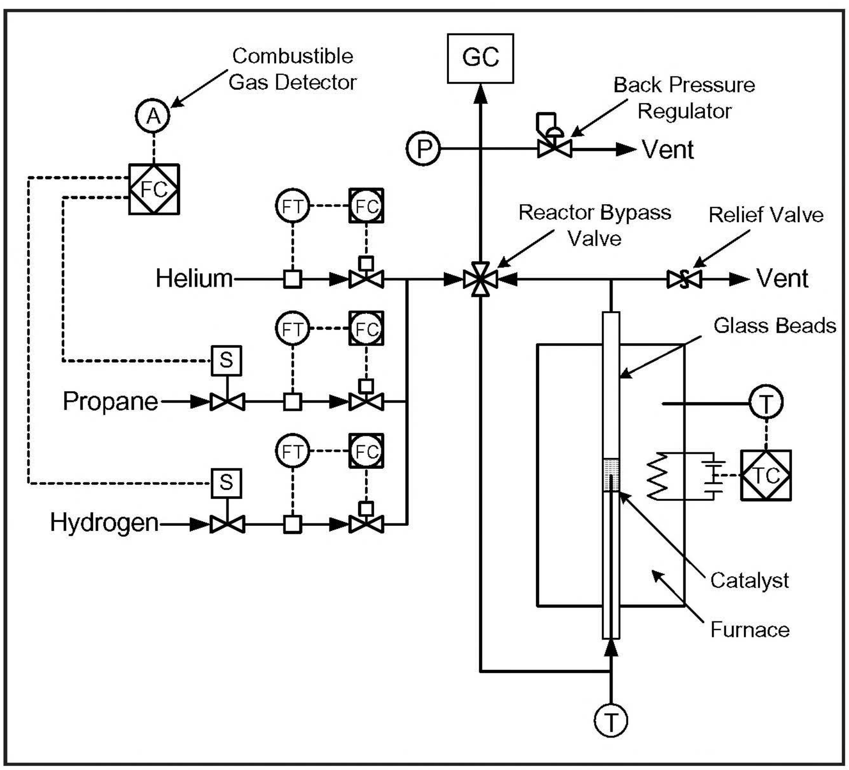

Figure 1. *Schematic for kinetics experiment apparatus.*

Due to the flammability of the reagents used in this experiment, a combustible gas detector with accompanying alarm system (RKI Instruments, Inc.) is used to detect process leakage of hydrocarbon reactants and reaction products. The concentration of gaseous hydrocarbons is detected by a fixed-mount, continuous-monitoring detector head that displays the current concentration of combustible gases and transmits this information electrically (4-20 mA signal) to a multichannel gas monitor. The gas monitor is programmed to sound an alarm if hazardous levels of combustible gas are detected and to simultaneously de-energize (close) the solenoid valves connected to the propane and hydrogen pressure regulators.

Gas analysis is achieved using a Varian CP-3380 gas chromatograph equipped with a Valco 6-port gas-sampling valve actuated using a Valco 3-way solenoid valve manifold, and a flame ionization detector that uses hydrogen and compressed air. Separation is achieved using helium carrier gas flow through a 213-mm by 3.2-mm stainless steel column packed with 80/100-mesh poropak

Q and maintained at 170°C. This gives well-separated peaks for the three hydrocarbons within an elution time cycle of only 2 minutes. A software package (CP-3800) obtained from Varian is used with a computer to operate the GC, perform data logging/peak area determination, etc. Exit streams from both the reactor and the GC are vented through tubing to the outside.

EXPERIMENTAL PROCEDURE

Before giving a general description of the procedure used, a few comments on how UOL is conducted at Clemson should be mentioned to provide proper context. The first is that, in contrast to many other laboratory courses that involve what is often called a "cookbook" approach, here each lab group (which consists of three or four students) writes a preliminary (pre-experiment) report as well as a final report. Prior to writing the preliminary report, each group is given a lecture on the topic, a brief "walk-through" of the apparatus, an assignment sheet outlining the objectives, and a handout that provides guidance regarding the use of the software and the safe operation of selected items of equipment, *e.g.,* the GC, flow and temperature controllers, and the combustible gas detector. The last of these handouts is felt to be necessary because of the complexity of the reactor system.

Once the group has received information about the experiment, they are required to submit the preliminary report, which contains

- *A schematic and an experimental plan, i.e., a fairly detailed listing of operational steps and safety issues*
- *Data tables*
- *Sample calculations*
- *Literature review*

This report is then read, graded, and corrected by the supervising faculty member and returned to the group. A group normally begins actual experimentation the next lab period after the graded preliminary report has been returned.

Depending on the background of the students, the instructor can assign students to develop a classical or a factorial design of experiments. Traditional methods would involve students evaluating one variable at a time (*e.g.,* all variables are held constant during a set of experiments, except for the variable being evaluated). Greater sampling efficiency and complexity of data analysis are achieved, however, by having students use the statistics-based strategy known as *design of experiments* to develop a factorial design that will enable them to quantify each parameter in the selected reaction model. For example, the combined power law/Arrhenius law model contains four parameters that need evaluating (α, β, E, k_o), while a Langmuir-Hinshelwood model incorporating the effect of temperature has a total of five parameters (a, E, k_o, ΔH_p, K_A). It should also be noted that using factorial designs often necessitates the use of nonlinear least-squares methods to obtain optimal values of kinetic parameters; hence, more sophisticated mathematical software programs may be required to complete data analysis. Discussions in this paper focus on traditional experiment designs and we would direct the reader to the literature for a detailed discussion of *design of experiments.*[7]

The first steps in the experimental procedure are to turn on the combustible-gas-detector system, start flow of a mixture of helium (160 sccm) and hydrogen (160 sccm) to the reactor, set the reactor pressure to 5 psig (135 kPa), and adjust the setpoint of the temperature controller to obtain a catalyst bed temperature in the 460 to 495°C range. Once a temperature in this range is obtained, reduction of the catalyst is continued for roughly 1 hour; then the reactor temperature is lowered to the desired value for the first propane hydrogenolysis run, typically in the 310 to 340°C range. During this time, GC operation is initiated by setting flows of helium carrier to the column and both hydrogen and air to the flame ionization detector (FID). Next, propane is added to the reactor feed stream and the flowrates of the three components (C_3H_8, H_2, He) are set to the desired values. Hydrogen is fed in considerable excess (H_2/C_3H_8 molar ratio ≥ 6) in order to minimize deactivation due to coking. A typical feed mixture for a run might consist of 20 sccm C_3H_8, 160 sccm H_2, and 160 sccm He, corresponding to roughly 6 mole % C_3H_8, 47% H_2, and 47% He.

For the conditions associated with the sets of runs described below, propane conversions are generally in the 2 to 10% range; thus, the reactor can be approximated as being a "differential reactor." Additionally, the selected flowrates, reactor temperature, and catalyst particle size ensure that the reactor pressure is axially uniform and are similar to conditions for which literature sources state that mass transfer effects did not distort the intrinsic kinetics.[5,6] As will be discussed later, these approximations greatly simplify data analysis, leading to the determination of kinetic parameters.

When students are asked to determine power law kinetic parameters, the first set of runs will commonly focus on determining the propane reaction order (α) value. To collect data for these calculations, exit gas GC peak-area values are recorded for a range, *e.g.,* 10 to 30 sccm, of propane feed rates (and thus propane concentrations, C_p, or partial pressures, P_p), at constant reactor temperature and pressure. At the same time, the hydrogen concentration (or partial pressure) is held virtually constant by adjusting the helium flow such that total flow remains constant.

The aforementioned use of a great excess of H_2, as well as differential reactor operation, facilitates isolating the effect of C_p on the rate of consumption of C_3H_8, $-r_p$. For a given set of conditions, successive runs (typically two to four) are made to confirm that the data are reasonably reproducible.

In the second set of runs, data for the determination of the hydrogen reaction order (β) are acquired by varying the hydrogen feed rate (and concentration, C_{H_2}) at the same reactor temperature, pressure, and total flow, while using a constant feed C_p value. Occasionally, a second method for varying C_{H_2} is used, namely, varying the reactor pressure at a given H_2 feed rate, to obtain data for comparison with that of the first method.

The third set of runs examines the temperature dependence of the rate, specifically the activation energy, E, and the pre-exponential (frequency) factor, k_o, that appear in the Arrhenius expression for the specific reaction rate, k (*i.e.,* $k = k_o e^{-(E/RT)}$). In this part of the experiment, the pressure and feed composition are usually held constant, while the reactor temperature is varied in increments of 5 to 7 C° over an appreciable range, *e.g.,* from 310 to 340°C.

The experiment as described takes two to three 3-hour periods that occur several days apart. Thus, it is important that the system be shut down after the first period and restarted for the second period in such a way that the catalyst's activity is unchanged. Shutdown is accomplished by first stopping propane flow while continuing to feed hydrogen and helium for at least fifteen minutes at the last temperature used, then lowering the reactor temperature set point to 0°C. This purges the reactor of any adsorbed propane. During this interval, power to the GC/computer is cut off and flows of H_2, He, and air to the GC are discontinued. Finally, power is cut off to the furnace, flow controllers, etc.

In order to achieve some diversity over a semester, the assignment (and thus the associated procedure) is often modified. In one such variant, the third set of runs is not devoted to determining the temperature dependence, but is used to study how well the reaction-rate expression developed from differential reactor operation at a constant temperature predicts integral packed-bed reactor behavior. In this case, the third set of runs involves conditions that give appreciably higher propane conversions, *e.g.,* 20 to 40%. Another variation involves students conducting experiments to determine parameters for a Langmuir-Hinshelwood model of the reaction process. A more detailed discussion of these experiments is provided in the data analysis section of this paper.

DATA ANALYSIS

As mentioned earlier, a group's preliminary report must address not only the procedure, but also the specific calculations and data analysis needed. The latter, in addition to being necessary for composing the final report, "shape" the experimental strategy by identifying the means by which the effect of a given variable can be isolated from that of others. The first portion of this section will describe data analysis for the simplified case of "power law kinetics." Later, a description is given outlining how this approach can be extended to deal with Langmuir-Hinshelwood rate equations. Before detailing how the power law kinetic parameters (α, β, E, k_o) are obtained, some background information will be provided.

Combining the rearranged propane balance for a packed-bed reactor with a power law approximation for the rate expressions gives

$$\frac{dF_p}{dW} = \frac{F_{po} dX_p}{dW} = -r_p = k_o e^{-\frac{E}{RT}} C_p^{\alpha} C_{H_2}^{\beta} \quad (2)$$

where F_p is the propane molar flow rate, W is the weight of catalyst, F_{po} is the propane molar feed rate, X_p is the propane fractional conversion, R is the gas constant, and T is the reactor absolute temperature.

For differential reactor operation, Eq. (2) can be approximated as a much simpler finite difference equation

$$\frac{F_{po} X_p}{W} = -r_p = k_o e^{-\frac{E}{R\overline{T}}} \overline{C}_p^{\alpha} \overline{C}_{H_2}^{\beta} \quad (3)$$

where $\overline{T}$ is the virtually uniform temperature of the entire catalyst bed, and $\overline{C}_p$ and $\overline{C}_{H_2}$ are average concentration values for the respective species, which, for the very low conversions used, differ only slightly from either the feed or exit values. Before going further with the illustration of how Eq. (3) was used, two clarifying comments should be made. The first is that, although the use of low X_p values makes data analysis easier, it also introduces considerable relative uncertainty into the determination of X_p by the conventional method, *i.e.,* comparing the inlet and outlet GC peak areas for propane. To avoid this problem, a more accurate method for converting GC data to X_p values was used. This involved using the exit gas GC peak areas and FID response factors for C_3H_8, C_2H_6, and CH_4, along with a carbon atom balance. The second comment regarding Eq. (3) is that, over the modest ranges of temperature and pressure studied, the irreversible power law expression is a reasonable approximation for the "true" rate equation.

Taking logarithms of both sides of Eq. (3) gives the "linearized" equation

$$\ell n(-r_p) = \ell n(k_o) - \frac{E}{R\overline{T}} + \alpha\, \ell n(\overline{C}_p) + \beta\, \ell n(\overline{C}_{H_2}) \quad (4)$$

One option for evaluating the power law kinetic parameters, α, β, E, and k_o, is to conduct a series of experiments in which the rate is found for various combinations of $\overline{T}$, $\overline{C}_p$, and $\overline{C}_{H_2}$, and then use nonlinear least-squares software to extract the values from the entire data set. An optimal data set can be collected using experimental conditions obtained from a factorial design (or other design of experiments approach) that has been optimized for the variables of interest. This approach, while nominally viable and easy to implement, is, for several reasons, less desirable than the more structured approach associated with the experimental procedure described earlier. The first reason is that the inelegant (and, often, less reliable) "collective least squares" regression approach does not require the students to form their experimental plan in a logical fashion, *e.g.,* devise a sequence of experimental (and computational) steps. A second reason is that it does not provide an opportunity to apply model development techniques that are central topics in most kinetics texts.[2]

The data analysis strategy actually used by many groups is one that is a logical follow-up to the experimental procedure. It will now be illustrated for the simple power-law case using data/results taken from a representative UOL report. For the first set of runs, where $\overline{C}_p$ was the only independent variable, Eq. (4) simplifies to

$$\ell n\left(-r_p\right) = \alpha\ \ell n\left(\overline{C}_p\right) + C_1 \tag{5}$$

where C_1 is a constant. The value of α is found as the slope of a plot such as that seen in Figure 2. In the particular case shown, a value of 1.3 was found for α, which is above the 0.8 to 1.0 range found in the literature[3-6] for this reaction over Pt/Al_2O_3. Over the past two years, other UOL groups have reported values ranging from 1.2 to 1.4. A representative sample of power-law kinetic parameters obtained by undergraduate students during the past two years is shown in Table 1. For the report whose results are being used as an example, a value of about -1.5 for β was found from a similar plot of $\ell n(-r_p)$ versus $\ell n(\overline{C}_{H_2})$ using data from the second set of runs, where $\overline{C}_{H_2}$ was the only independent variable. This value is within the -1.3 to -3 range reported in the literature and clearly shows the expected inhibiting effect of hydrogen adsorption. Other UOL groups reported β values ranging from -0.6 to -1.7.

Once the separate orders of reaction are known, the k_o and E values are found by first calculating specific reaction rate (k) values for each of the temperatures used in the third set of runs, where all concentrations and flow rates were held constant, and then constructing an "Arrhenius plot" such as Figure 3. The calculation of k is accomplished using

$$k = k_o e^{\frac{-E}{R\overline{T}}} = \frac{-r_p}{\overline{C}_p^{\alpha}\ \overline{C}_{H_2}^{\beta}} \tag{6}$$

from which it can be seen that the slope of a linear plot of $\ell n(k)$ versus $\overline{T}^{-1}$ equals -E/R and the intercept as $T \to \infty$ equals $\ell n(k_o)$. The results of Figure 3 correspond to $E \approx 164$ kJ/mole (39 kcal/mole) and $k_o \approx 8.5 \times 10^9$ moles$^{1.2}$/(cm$^{0.6}$ · g catalyst.min). This activation energy is slightly lower than the 188 to 208 kJ/mole range reported by other investigators.[3-6] As shown in Table 1, other UOL groups found E values ranging from a clearly too-low value of 93 kJ/mole to a reasonable value of 194 kJ/mole. It should also be noted that the same catalyst sample was used for all studies having data reported in Table 1.

If one wishes to use a Langmuir-Hinshelwood model, one of numerous possibilities is a model proposed by Leclerq, *et al.*,[3] that assumes that the rate-controlling step is surface reaction between $C_3H_{x,ads}$ and either gaseous H_2 or associatively adsorbed H_2 to form C_2H_y and CH_z, which are rapidly hydrogenated to (and desorbed as) C_2H_6 and CH_4. Single site adsorption (with $C_3H_{x,ads}$ being the predominant surface species) is assumed. The rate expression in this case is

$$-r_p = k\frac{K_1\overline{C}_p\overline{C}_{H_2}}{\overline{C}_{H_2}^{a} + K_1\overline{C}_p} \tag{7}$$

where k is the pseudo surface reaction rate constant, K_1 is the propane equilibrium adsorption constant, and a = 4 - x/2. Note that if $\overline{C}_{H_2}^{a} >> K_1\overline{C}_p$, this simplifies to a power-law equation, *i.e.*, $-r_p \approx k^*\overline{C}_p\overline{C}_{H_2}^{1-a}$. For the experimental results discussed above, where a value of -1.5 for β (=1-a) was found, the value for "a" would be 2.5. If accurate, this would imply that, on average, propane loses five H atoms upon adsorption and that the most probable values for y and z are 3 and 2, respectively. The proposed mechanism leading to this rate equation is summarized by the following elementary steps where "site" refers to an unoccupied surface site, "ads" implies adsorbed, and y + z = x + 2 = 10 - 2a:

- C_3H_8 + site $\Leftrightarrow (C_3H_{8-2a})_{ads} + aH_2$: *fast, with equilibrium constant K_1*
- $(C_3H_{8-2a})_{ads} + H_2 \rightarrow (C_2H_y)_{ads} + (CH_z)_{ads}$: *slow, rate-controlling*
- $(C_2H_y)_{ads} + (CH_z)_{ads} + H_2 \rightarrow C_2H_6 + CH_4$: *fast*

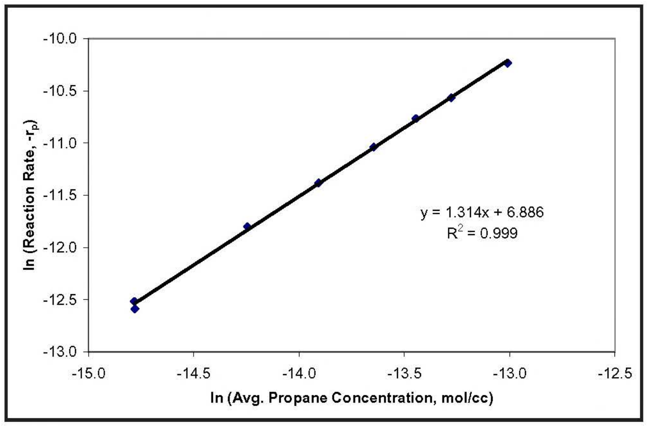

Figure 2. *Determination of propane reaction order (α).*

TABLE 1
Representative Power-Law Kinetic Parameters Calculated from Experimental Data Collected by Undergraduate Students

Experiment Date	*E(kJ/mol)*	α	β
9-23-02	185	1.3	-1.7
10-14-02	194	1.3	-1.5
11-11-02	164	1.2	-1.4
12-3-02	157	1.4	-1.2
4-1-03	164	1.3	-1.5
11-3-03	145	1.4	-0.6
12-3-03	93	1.3	-0.8

The specific rate equation shown above can be rearranged to give

$$\frac{\overline{C}_p \overline{C}_{H_2}}{-r_p} = \frac{\overline{C}^{\,a}_{H_2}}{k K_1} + \frac{\overline{C}_p}{k} \tag{8}$$

which, for a given assumed value of "a", should give a straight line when $-r_p^{-1}\overline{C}_p\overline{C}_{H_2}$ is plotted versus $\overline{C}^{\,a}_{H_2}$ for data taken at constant $\overline{C}_p$ and temperature. The best-fitting value for "a" can be found by varying $\overline{C}^{\,a}_{H_2}$ over the maximum practicable range and examining the resulting least squares correlation coefficient (R^2) values. Next, the k value can be determined from the intercept, *i.e.,* $k^{-1}\overline{C}_p$, and then the K_1 value can be found from the slope, *i.e.,* $(k K_1)^{-1}$. An alternative (or supplemental) method is to use data taken at constant $\overline{C}_{H_2}$ and temperature, with $\overline{C}_p$ intentionally varied. In that case (for a given assumed "a" value), the k and K_1 values can be found from the intercept $(k\overline{C}_{H_2})^{-1}$ and slope $(k K_1)^{-1}\,\overline{C}^{\,a-1}_{H_2}$ of a least squares fit of $-r_p^{-1}$ versus $\overline{C}_p^{-1}$.

Assignments involving the use of Langmuir-Hinshelwood kinetics could range in difficulty from a case similar to the one just illustrated (where parameter evaluation is for a single given mechanism with the assumed rate-controlling step specified) to a challenging case in which the best-fitting mechanism/controlling step must be determined from a variety of proposed explanations/hypotheses. Students could also be asked to assume a specific Langmuir-Hinshelwood model and collect data to determine the activation energy, E, and frequency factor, k_o, for the reaction as well as a heat of adsorption, $-\Delta H_p$, for propane using an integrated form of van't Hoff's expression for the equilibrium adsorption constant,

$$K_1,\ i.e.,\ K_1 = K_A e^{-\Delta H_p/R\overline{T}}$$

where K_A and ΔH_p are independent of temperature over the range studied.

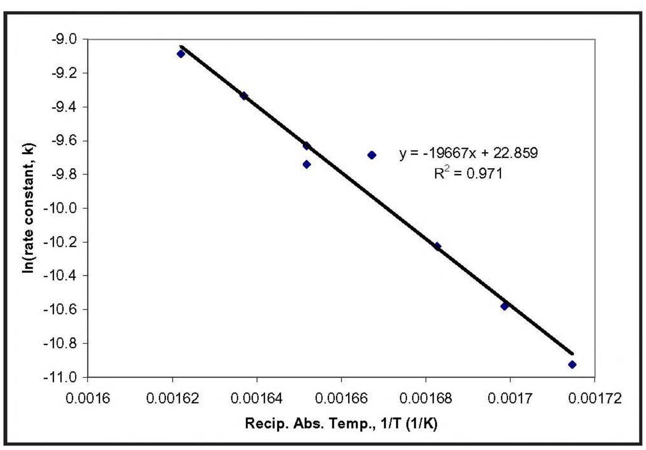

Figure 3. *Arrhenius plot for determining frequency factor and activation energy for the Pt-catalyzed hydrogenolysis of propane.*

CLOSING REMARKS

In this paper we have attempted to not only describe the apparatus and procedure used for our recently implemented kinetics experiment, but also to provide a rationale for its design and a sampling of results. The experiment offers students the opportunity to devise a workable plan for accomplishing a relatively challenging assignment (which can include developing a factorial design of experiments) and then to observe firsthand the effect of important variables (space time, feed composition, temperature) on the rate of a catalyzed reaction. In carrying out the experiment, students become familiar with up-to-date instrumentation and, in writing the final report, they employ a variety of numerical methods to obtain/analyze their results.

The primary advantage of the described kinetics experiment is its flexibility. The assignments can be kept simple and straightforward (*e.g.,* use classical methods to determine reaction order and activation energy values for a power-law model) or students can be challenged to develop a factorial design to efficiently determine all kinetic parameters for a Langmuir-Hinshelwood model that uses an Arrhenius law expression to describe variations in rate with temperature. Further, minimal changes to the reactor system would be required to have students examine other catalysts or gas-phase reactions (*e.g.,* hydrogenation of propene).

ACKNOWLEDGMENTS

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USING A WEB MODULE TO TEACH STOCHASTIC MODELING

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Computational modeling in chemical engineering is becoming more and more a field in its own right, due largely to the rapidly increasing power of computers but also because of progress being made in developing numerical algorithms, which are necessary to solve sophisticated models.

The industry is highly interested because computer simulations have significantly lower costs compared to experimental studies. Some important ingredients for the field include accurate physical and chemical models in mathematical form, numerical values for the parameters that occur in these models (either taken from carefully selected experiments or from first-principles calculations), fast computers, efficient and powerful numerical methods, and—most importantly—competent engineers who are aware of the limitations of the models, parameters, and numerical methods.

Although important, the whole field of computational engineering is far too rich to be taught in a single course. In this article we discuss the teaching of stochastic (or "Monte Carlo") methods to students of chemical engineering. Monte Carlo methods have been shown to be highly efficient in many applications and can be found in various areas in the process and chemical industry, such as polymer synthesis, crystallization, liquid-liquid extraction, etc. They are also useful when it comes to simulating turbulent flames and their emissions as well as aerosol transport in the atmosphere. More generally, it has been demonstrated in some cases that stochastic models can account for effects that the corresponding deterministic models cannot. This is because fluctuations can sometimes significantly change the overall behavior of nonlinear physical models.

Another important aspect of Monte Carlo methods is, in our opinion, the connection to mathematics—which provides an appropriate language by means of the theory of stochastic processes. In the last decades a number of important mathematical results have been achieved that shift Monte Carlo methods from an intuitive, naive modeling level to the rigorous mathematical discipline of interacting stochastic-particle systems and their corresponding limit equations. A class of stochastic processes which is relevant for chemical engineering is Markov processes, in particular jump and Wiener processes (Brownian motion). To the best knowledge of the authors, so far in chemical engineering the subject has been taught from an intuitive point of view, focusing mainly on the physical motivation of the model. Examples can be found

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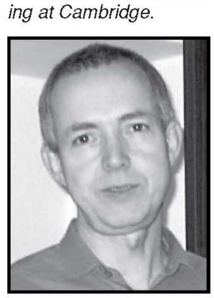

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in reference one as well as in the course CH 235 (AUG) 3:0 in the masters program taught at the IISc-Bangalore (<http://www.iisc.ernet.in/soi/ch.htm>), which is based in parts on the book by D.M. Himmelblau and K.B. Bischoff, *Process Analysis and Simulation*, first published by John Wiley in 1967.

With this in mind the authors felt a need to design a course to bridge the gap between the *physical*—say, direct simulation methods—and the more rigorous *mathematical* approach. First, we aim to enable students to understand current Monte Carlo methods on a more fundamental level and also to help them improve a given Monte Carlo method in terms of its numerical efficiency. Second, we teach students the connections between deterministic models and their stochastic counterparts given by a Monte Carlo algorithm.

A first result of the authors' activity is the 16-lecture course taught in the Department of Chemical Engineering at the University of Cambridge. The course, named Stochastic Modeling in Chemical Engineering, is given to students who are at an advanced undergraduate/beginning postgraduate level in the last (fourth) year of the undergraduate curriculum. At that stage, students have already been exposed to some computational techniques in process engineering, and they have a solid knowledge of models used in chemical engineering.

We demonstrate, while looking at a particular example, how a stochastic process can be obtained from its Master equation and discuss how Monte Carlo algorithms can be implemented on a computer.

The stochastic modeling course starts with examples in chemical engineering that lend themselves to a stochastic approach. After the introduction, we discuss how random numbers can be obtained using numerical algorithms. Then the notion of a Markov process is introduced, and the particular example of a jump process (death process) is examined.

Using this basis, we then develop a jump process that can be used to model a perfectly mixed gas in a tank reactor. For this system, a Direct Simulation Monte Carlo (DSMC) method is introduced that simulates how the physical quantities of interest change with time. The DSMC algorithm is based on the work of Gillespie[2, 3] published in the 1970s. We demonstrate, while looking at a particular example, how a stochastic process can be obtained from its Master equation and discuss how Monte Carlo algorithms can be implemented on a computer. For this algorithm, we present techniques for investigating numerical properties of Monte Carlo algorithms in general.

We then generalize the DSMC algorithm to arbitrary systems of ordinary differential equations (ODEs) and study coagulation of particles as described by the Smoluchowski equation.[4]

Finally, we introduce stochastic reactor models, which account for nonideally mixed chemical reactors. These models are based on the joint scalar probability density function transport equation, which is also frequently used for modeling turbulent reacting flow.

For all examples, we state a DSMC algorithm that can be easily implemented on a computer. The lectures are accompanied by example papers, which are discussed in small, supervised groups. These example papers are pencil and paper problems in a classical fashion; they do not contain any programming exercises, which would have to be carried out on a computer. This is partly because the students have not been taught a high-level computer language such as FORTRAN or C, and also because the implementation of algorithms as part of computer science does not provide any insight from the modeling perspective. The overall assessment of the students' learning progress is at the end of the academic year, when they have to complete four papers that cover all the courses taught in that year.

To introduce an element of continuous assessment and to give students the possibility of getting some working experience with stochastic algorithms, the stochastic modeling course is complemented by a Web module, which will be described in more detail later in this paper. The purpose of this Web module is to let students gain some experience on how to perform and investigate a Monte Carlo simulation algorithm without assuming any knowledge of a programming language.

The Web module can be accessed from every computer that runs Microsoft Internet Explorer or a similar Java-enabled browser. All students at Cambridge (and a large proportion of students worldwide) have access to such computers either at home or on campus.

The Web module, as it has been set up, also introduces an element of continuous assessment. As described in more detail below, it contains a set of tasks and exercises, which students have to complete either in small groups or on their own. They are asked to summarize their results and send a short report by mail to the research assistant or the lecturer who accompanied the students' progress. Some students even completed their reports at home during the vacation period and kept in touch via e-mail.

The content and design of the Web module are described in detail in the next section, which refers to one particular part of the stochastic modeling course—that dealing with the direct simulation of chemical reactions in a perfectly stirred batch reactor. Two reactions are studied: a simple chemical reaction for efficiency and convergence analysis, and the Belousov-Zhabotinsky (BZ) reaction as an example of a chaotic chemical system. The well-known BZ system has been chosen to study the influence of fluctuations on chemical reactions. Furthermore, it presents an example of an oscillating reaction and aims to illuminate how such a system can be studied analytically using local stability analysis. In various exercises involving a number of numerical experiments with the Java applet, students have the opportunity to develop an understanding of the chemical reactions and see how the theoretical analysis is related to the actual behavior of the system.

We hope that by making this teaching resource available on the Internet we can encourage other university teachers to use it as an addition to their lecture courses. In our opinion, the module is not limited to chemical engineering courses but might also be useful in all physics, chemistry, or mathematics courses that contain elements of stochastic processes and/or nonlinear ordinary differential equations.

DESCRIPTION OF THE WEB SITE

The Web module can be accessed through the home page of the course "Stochastic Modeling in Chemical Engineering," < http://www.cheng.cam.ac.uk/c4e/StoMo>, or directly via <http://www.cheng.cam.ac.uk/c4e/WebModule>. The site is structured as follows: On the title page, the table of contents is shown in the form of links to all subsequent pages. Furthermore, at the top and bottom of every page there are navigational buttons, so that the user is led through the whole site step by step. The following pages can be found:

- *Introduction*
- *Theory*
  - *Some theory for a simple example*
  - *Some theory for the Belousov-Zhabotinsky system*
- *Algorithms*
  - *Algorithm for the simple example*
  - *Algorithm for the Belousov-Zhabotinsky system*
- *Numerical experiments*
- *Videos of actual experiments*
- *Questionnaire*
- *Web-based teaching—a survey*
- *Bibliography*

On the introductory page, we explain the subjects and the aims of the Web module and its connections to other teaching units. We focus on three areas: reaction engineering, Monte Carlo methods, and dynamical systems and chaos. We discuss how the Web module is related to these areas. And we specifically state the aims we want to achieve, which are:

1. *To provide a numerical tool, based on a Monte Carlo method, to simulate chemical reactions and understand the numerical properties of Monte Carlo methods for chemical reactions*
2. *To study a chemical reaction system analytically using linear stability analysis*
3. *To present an example for oscillating reactions and chemical feedback*

The Connection to Other Teaching units are specific to the chemical engineering course in Cambridge, but these courses are taught in similar fashion in other chemical engineering departments the world over. Curriculum containing materials that provide the basis for the modules' successful use and the problems' completion includes: Computer-Aided Process Engineering, Statistics, Mathematical Modeling of Chemical Reactors, Combustion, Bioprocess Engineering, Thermodynamics, and Kinetic Theory.

In the theory section, we introduce two example systems to be considered. The first consists of two very simple chemical reactions, allowing students to focus on investigating numerical properties of the algorithm rather than struggling with the complexity of the system itself. In the second, students are familiarized with the BZ reaction in some detail, but in order to avoid confusion, we restrict ourselves to a simplified oregonator mechanism due to Field, Körös, and Noyes.[5, 6]

$$A + Y \xrightarrow{k_3} X + P$$

$$X + Y \xrightarrow{k_2} 2P$$

$$A + X \xrightarrow{k_5} 2X + 2Z$$

$$2X \xrightarrow{k_4} A + P$$

$$B + Z \xrightarrow{k_c} \frac{1}{2} fY$$

Here, X, Y, and Z are the species of interest in which the oscillations are to be observed, A and B are assumed to be constant, and f is an adjustable (not necessarily integer) parameter which arises due to the simplification of the model. By performing a transformation of variables[7] on the corresponding reaction-rate equations, we derive a system of three dimensionless ordinary differential equations:

$$\frac{dx}{d\tau} = \frac{1}{\varepsilon}\left[qy - xy + x(1-x)\right]$$

$$\frac{dy}{d\tau} = \frac{1}{\varepsilon'}\left[-qy - xy + fz\right]$$

$$\frac{dz}{d\tau} = x - z$$

The dimensionless parameters ε, ε', q, and f, which are functions of A, B, and the rate constants, determine the qualitative dynamical behavior of the system. Specifically, students are led through the calculation of the steady state and the so-called nullclines, which, using a number of graphs, provides an intuitive understanding of the time evolution in the phase space. Finally, we demonstrate how to perform a local stability analysis by means of linearization at the point of steady state including a classification of the eigenvalues of the Jacobi matrix.

On the algorithm pages, we write down explicitly the stochastic algorithms for both systems of chemical reactions. This is simply a specialization of the general method presented in the lectures, using the same notation, and is furthermore identical to Gillespie's method.[2, 3] As mentioned above, instead of referring to a particular programming language, we describe in words and formulae every step of the algorithm. In the lecture course, students have learned the concepts of reaction-rate functions (or simply, rates) $\tilde{K}_i$, waiting time parameter

$$\pi = \sum \tilde{K}_i$$

and reaction probabilities $p_i = \tilde{K}_i / \pi$. Equipped with this knowledge, students are well prepared to understand the algorithms. The one for the BZ system reads:

1. *Initialize the number of particles for each species, i.e., N_X, N_Y, and N_Z, set the time t equal to zero, and fix a stopping time t_{stop}.*
2. *Calculate the rates $\tilde{K}_i$, the waiting time parameter π, and the reaction probabilities p_i.*
3. *Generate an exponentially distributed waiting time τ, where the decay constant of the exponential is given by the waiting time parameter π. Generate a reaction index α according to the reaction probabilities p_i.*
4. *Perform the reaction α chosen in the previous step, i.e.:*
   - *If $\alpha = 1$ then increase N_X by 1 and decrease N_Y by 1*
   - *If $\alpha = 2$ then decrease N_X and N_Y each by 1*
   - *If $\alpha = 3$ then increase N_X by 1 and N_Z by 2*
   - *If $\alpha = 4$ then decrease N_X by 2*
   - *If $\alpha = 5$ then increase N_Y by f/2 and decrease N_Z by 1*
5. *Advance the current time t to $t + \tau$. If $t < t_{stop}$, go to step 2; otherwise stop.*

The description of the Java applet and the list of exercises are a central part of the Web site. The corresponding page first explains the purpose of the applet, then its elements and parameters, how to run a simulation, and how to obtain measurement data. The applet can be started by clicking on a link that opens a new window containing just the applet, so that students can run simulations and browse the Web site at the same time. Figure 1 shows the program with a typical output of the time evolution of the species, the phase space diagram, and numerical measurement data. It might be necessary to download the Java 2 Runtime Environment plug-in to view this page (the page has been tested using version 1.3.1_03).

Apart from experimenting with the applet in a rather unsystematic way, we expect students to complete a number of problems and exercises. The students who participated in the lecture course were asked to include answers to the problems in an essay to be handed in for grading.

The exercises focus on three areas: the numerical properties of the stochastic algorithm, the physical properties of the BZ system, and the characteristic features of dynamical systems. On the numerical side, students are asked to study systematic and statistical errors, their convergence, and some efficiency-related issues using the simple system of chemical reactions as a test case. Then, by investigating the BZ system, the theoretical knowledge on dynamical systems developed earlier is to be consolidated. Feedback on the reports was given in supervisions, which are tutorials for groups of two to three students (typical for the Cambridge system of education). In some cases students contacted research assistants through e-mail to ask specific questions.

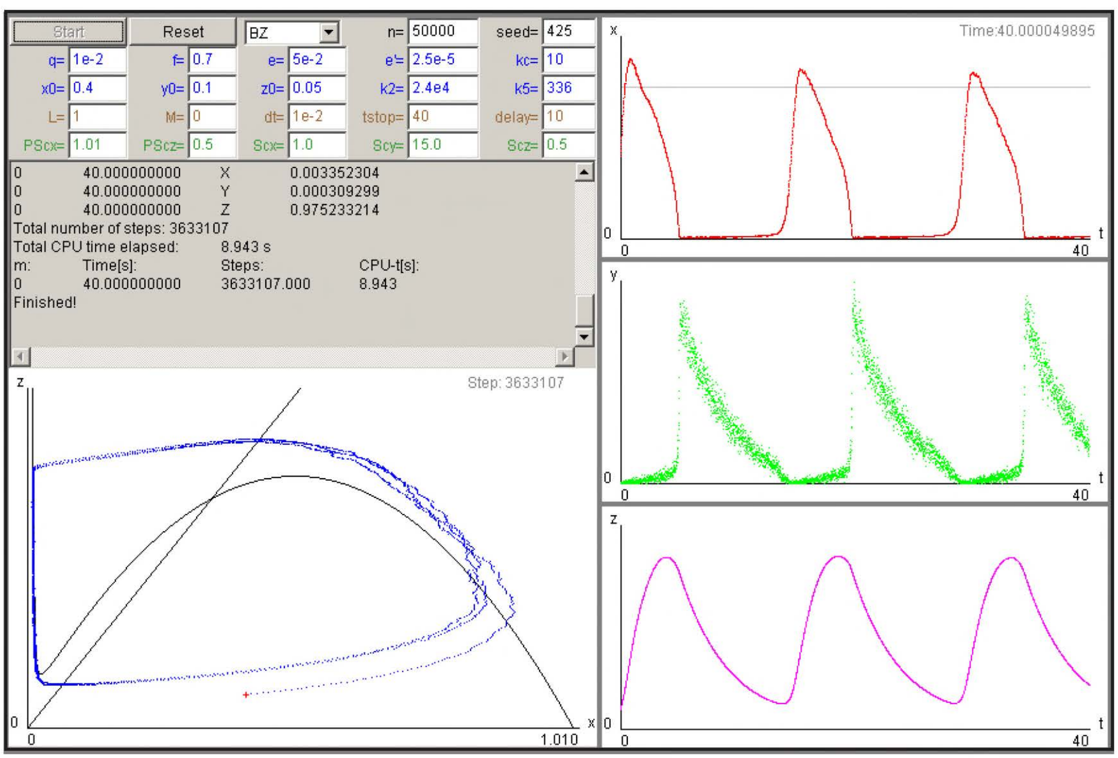

Figure 1. Screenshot of the Java applet in action.

For motivational purposes, we include an extra page with links to videos of BZ-reaction experiments. These videos were not produced by the authors, but they do complement the Web module, since running the Java applet can qualitatively reproduce the behavior of these experiments.

Lastly, the students can give feedback by completing an online evaluation form. We compiled a number of questions to gather information on how to improve the Web module for the next academic year. Different criteria are evaluated, including technical usability, organization of content, and quality of the problems and exercises. Students answer each question by choosing a number from 1 to 5. We also ask how long it took them to complete the problems, in order to estimate how to alter or add exercises in the future. In text boxes, we offer the opportunity to give more detailed feedback. Users can identify strengths and weaknesses of the Web module and comment on the Internet-based teaching approach in general.

On the page titled "Web-based teaching—a survey" we list a number of Web sites that also attempt to supplement conventional courses. We do this mainly because during the design phase of this Web module, we came across many examples that we thought deserved some advertising. We distinguish between different classes of teaching material and give short descriptions of a selection of Web pages. More details on various aspects of the material presented can be found in references one and seven through 13, which are all included in the Web module.

EVALUATION

The course Stochastic Modeling in Chemical Engineering is an elective in the fourth year. Typically up to 10 students sign up for it. At the end of each lecture course the students answer a questionnaire to assess the course's content and technical issues. Most students indicate they enjoyed completing the stochastic-modeling Web module, in particular the hands-on aspect of numerical experimentation. Also highly rated is the aspect of modeling real chemical reactions as shown in the videos. Furthermore, students remarked that the structure of the Web module allowed them to concentrate on better understanding the material without having to worry about the fine points of computer programming. With the activity presented as a Web module, they were able to progress through it at their own pace, wherever they had access to a computer. Most of the students, however, complained about the amount of material and the shortage of time they had to complete the tasks.

CONCLUDING REMARKS

In this paper, we described the course development on stochastic numerical methods in chemical engineering at Cambridge and presented a Web module, which is a central part of the fourth-year course Stochastic Modeling in Chemical Engineering. This Web module allows students at Cambridge to practice concepts taught in lectures, and it offers students worldwide a practical tool for studying stochastic methods and nonlinear chemical systems. Two chemical reactions in a perfectly mixed batch reactor can be studied using a DSMC algorithm implemented in a Java applet.

In working through the Web module, the users are supposed to write an essay that includes answers to a set of problems given in the module. To obtain these answers, students need to make extensive use of the Java applet. The Web module contains some additional material on the chemical and physical background of the reactions being studied. It also provides some basic material on linear-stability analysis.

Some videos and a survey on Web-based teaching complete the Web module. An online questionnaire gives users the opportunity to comment on various aspects and suggest improvements.

We view this course as a first step into Web-based teaching. We are planning to increase the number of Web modules for this particular course, but also hope to begin a virtual laboratory. Funding for this activity has already been made available by the Cambridge MIT Institute (CMI), and first results will be published in due course.

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