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Chemical Engineering Division, American Society for Engineering Education

American Institute of Chemical Engineers

Margot Vigeant

. . . of Bucknell University

Feature Articles . . .

and ChE at . . .

The University of Tulsa

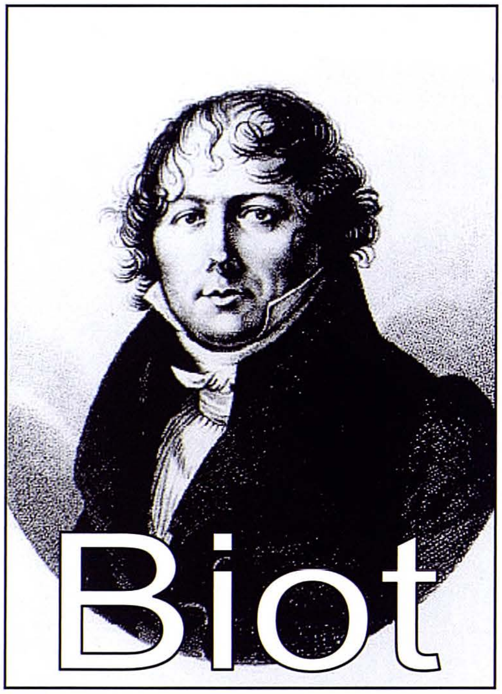
ChE teaching tips

OLD DEAD GUY TRADING CARDS

DAVID ROCKSTRAW
New Mexico State University, Las Cruces, NM 88003

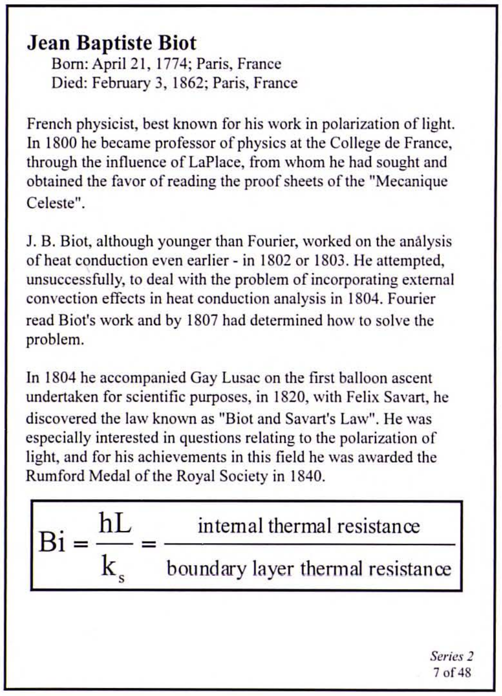
I planned to play for the Chicago Cubs. I was making great progress toward that goal at the age of seven when my baseball team won the championship in the summer of 1969. I was never on another championship team and my plans of a pro baseball career ended in high school. All that remained of my dream were hoarded shoeboxes of baseball cards. Today, the hall-of-famers whose cards I collected are becoming a collection of old dead guys.

As Holles[1] pointed out, "Old Dead Guys" make great subject matter for activity breaks in the classroom. While teaching Heat and Mass Transfer, I combined Holles' "Old Dead Guys" with my former hobby of card collecting to create a set of trading cards commemorating the scientists behind the dimensionless groups of transport phenomena, immortalizing the names that permeate chemical engineering texts: Reynolds, Nusselt, Fourier, Prandlt, Rayleigh, Peclet, Grashof, Sherwood, and Schmidt to name a few.



A pack of these old dead guy cards could not be purchased at the Five-&-Dime, rather they had to be earned, one card at a time. The card containing a photographic image of Jean Baptiste Biot on the front and his biography on the back could only be acquired by correctly noting on an exam that the Biot Number is the ratio of internal thermal resistance to boundary layer thermal resistance, quantified as the quotient of the film coefficient to the thermal conductivity of the body. In a similar manner, the Osborne Reynolds card could only be owned by correctly identifying that the Reynolds Number was the ratio of inertial to viscous forces, quantified as the product of mean velocity and hydraulic diameter, divided by the kinematic viscosity. The Biot was the first card awarded in the Fall 2002 semester when I first employed these cards as a motivational teaching tool. Only a handful of students came to class prepared to be the recipient of a J.B. Biot card, consequently there are only a few in circulation, making this card as rare as a T206 Honus Wagner baseball card.

Although I no longer teach Heat and Mass Transfer, the nerd cards (as lovingly named by the students) phenomenon continues among New Mexico State University chemical engineering students through the student chapter of AICHE. The deck has been expanded to 48 cards to include the "father" of chemical engineering George Davis[2] and other names common to the discipline such as Norton, Solvay, Haber, Bosch, Langmuir, and Arrhenius. The Series 2 deck also includes some old living guys well known within the profession for their textbooks. Only about a dozen of the Series 2 decks remain within the student chapter's coffers; most have been sold to current students, were made available to department alumni through Facebook and eBay, awarded as door prizes at chapter meetings, or given as gifts to alumni and dignitaries who give of their time to speak at a meeting of the NMSU AICHE Student Chapter. A planned Series 3 deck will further increase the list of names familiar to those in the discipline.



Jean Baptiste Biot
Born: April 21, 1774; Paris, France
Died: February 3, 1862; Paris, France

French physicist, best known for his work in polarization of light. In 1800 he became professor of physics at the College de France, through the influence of LaPlace, from whom he had sought and obtained the favor of reading the proof sheets of the "Mecanique Celeste".

J. B. Biot, although younger than Fourier, worked on the analysis of heat conduction even earlier - in 1802 or 1803. He attempted, unsuccessfully, to deal with the problem of incorporating external convection effects in heat conduction analysis in 1804. Fourier read Biot's work and by 1807 had determined how to solve the problem.

In 1804 he accompanied Gay Lusac on the first balloon ascent undertaken for scientific purposes, in 1820, with Felix Savart, he discovered the law known as "Biot and Savart's Law". He was especially interested in questions relating to the polarization of light, and for his achievements in this field he was awarded the Rumford Medal of the Royal Society in 1840.

$$\boxed{\mathrm{Bi} = \frac{hL}{k_s} = \frac{\text{internal thermal resistance}}{\text{boundary layer thermal resistance}}}$$

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2. Cohen, C., "The Early History of Chemical Engineering: A Reassessment," in *The British J. for the History of Science*, **29**(2), 171 (1996) ❐

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Chemical Engineering at . . .
The University of Tulsa

Geoffrey L. Price

Collins Hall and the main entry to the university.

When people think of Oklahoma, they often think of the Dust Bowl of the 1930s and images of drought, or perhaps Indian country with miles of undeveloped wilderness. As different as the modern Department of Chemical Engineering at the University of Tulsa is from such images, the department *was* founded in the 1930s and the university was originally a school for Native American girls, a heritage of which we are proud. We have become a high-quality program, perhaps slanted a bit toward undergraduate teaching, but certainly well balanced in teaching and research. We offer an ABET-accredited B.S. degree, a Master of Science degree (which is research-based), a Master's of Engineering in Chemical Engineering degree (which is coursework-based), and a Doctor of Philosophy (Ph.D.) degree.

THE UNIVERSITY SETTING

The University of Tulsa (TU) is a comprehensive, private university, providing education in Arts and Sciences, Business, Engineering and Natural Sciences, and Law. Our 200-acre campus is just a few miles east of downtown Tulsa. The campus is beautifully maintained with Tennessee ledgestone buildings throughout the site. Current enrollment is 3,084 undergraduate students and 1,103 graduate students (including Law), with one in 12 undergraduates being National Merit Finalists. With 306 full-time faculty, the student-to-faculty ratio is 11:1. Even with the relatively small number of students, the university competes in NCAA Division I sports.

TU is currently 75th in the *US News & World Report* college and university rankings, with virtually unparalleled dedication to small-class sizes. This is the highest ranking TU has ever received in this publication, and marks the ninth consecutive year that TU has been ranked in the top 100. The *Princeton Review* has named the university one of the nation's best institutions for undergraduate education, citing the school's "unequivocal emphasis on academics." The university recently completed a $698 million comprehensive fund-raising campaign that created program support, built infrastructure, and established student scholarships and faculty endowments. There were 54 endowed professorships on campus in 2010-11.

The Department of Chemical Engineering is one of 10 departments and schools in the College of Engineering and Natural Sciences (ENS). ENS is the largest of the colleges on campus with 1,195 undergraduate students enrolled in 2010-11. Currently housed primarily in Keplinger Hall, TU has embarked on a massive expansion that includes the addition of two new ENS buildings: J. Newton Rayzor Hall and Stephenson Hall. Rayzor Hall was completed in 2011 and will house the Electrical Engineering and Computer Science departments, and Stephenson Hall will be completed in 2012 and will house the McDougall School of Petroleum Engineering and Department of Mechanical Engineering.

Wilbur "Doc" Nelson, founder of the Chemical Engineering Department.

The Department of Chemical Engineering has nine full-time faculty. Undergraduate enrollment was 124 and graduate enrollment was 27 in the 2010-11 school year. Like many other chemical engineering programs around the country, the department has been growing in student numbers for the last seven years. Nonetheless, our student-to-faculty ratio has remained very low, and it is similar to the campus-wide ratio. Because of the low student-to-faculty ratio, the faculty are able to devote considerable effort to both undergraduate teaching and research. The historical trends in student population and B.S. graduates are given in Figure 1.

HISTORY

Looking back into the foundations of the Department of Chemical Engineering, an important day was Nov. 22, 1905. This was the date that the first drilling operation struck oil over what became known as the Glenn Pool, near the modern day city of Glenpool, OK, about 17 miles south of Tulsa. Glenpool is known as the town that made Tulsa famous. The drilling activity and oil production that escalated rapidly from the discovery of the Glenn Pool, which was the largest oil field known, spurred the growth of Tulsa, and Tulsa soon became known as the "Oil Capital of the World," a moniker it maintained through the 20th century.

Meanwhile, the Presbyterian School for Indian Girls, founded in 1882 in Muscogee (modern spelling "Muskogee"), OK, became Henry Kendall College in 1894, and moved to Tulsa in 1907. Because of the importance of oil in the area and the vast financial interests spawned by the oil industry, as Henry Kendall College grew in Tulsa many students, alumni, trustees, and supporters were involved in the oil industry. Henry Kendall College became the University of Tulsa in 1921.

The School of Petroleum Engineering at the University of Tulsa began in 1928. **Waite Phillips**—brother of **Frank Phillips**, the founder of Phillips Petroleum Company—donated money to build the first Petroleum Engineering building in 1929. **Wilbur L. "Doc" Nelson** joined the university as the first head of Petroleum Engineering in 1930, and in 1932 Petroleum Engineering was divided into production and refining entities, and Doc Nelson became head of Petroleum Refining. In 1937, two B.S. engineering degrees were offered at the University of Tulsa, in petroleum engineering and chemical engineering. Doc Nelson became head of the Chemical Engineering Department in 1939 when its modern name was taken. Nelson remained head of the department until 1954 and taught part-time through 1972.

Nelson is easily recognized as the person that brought the department to national and international prominence and is often called the founder of the department. The *Oil & Gas Journal* published more than 2,000 articles by Nelson, and his book *Petroleum Refinery Engineering* became the worldwide standard. The Nelson Index, an index that describes a measure of the complexity

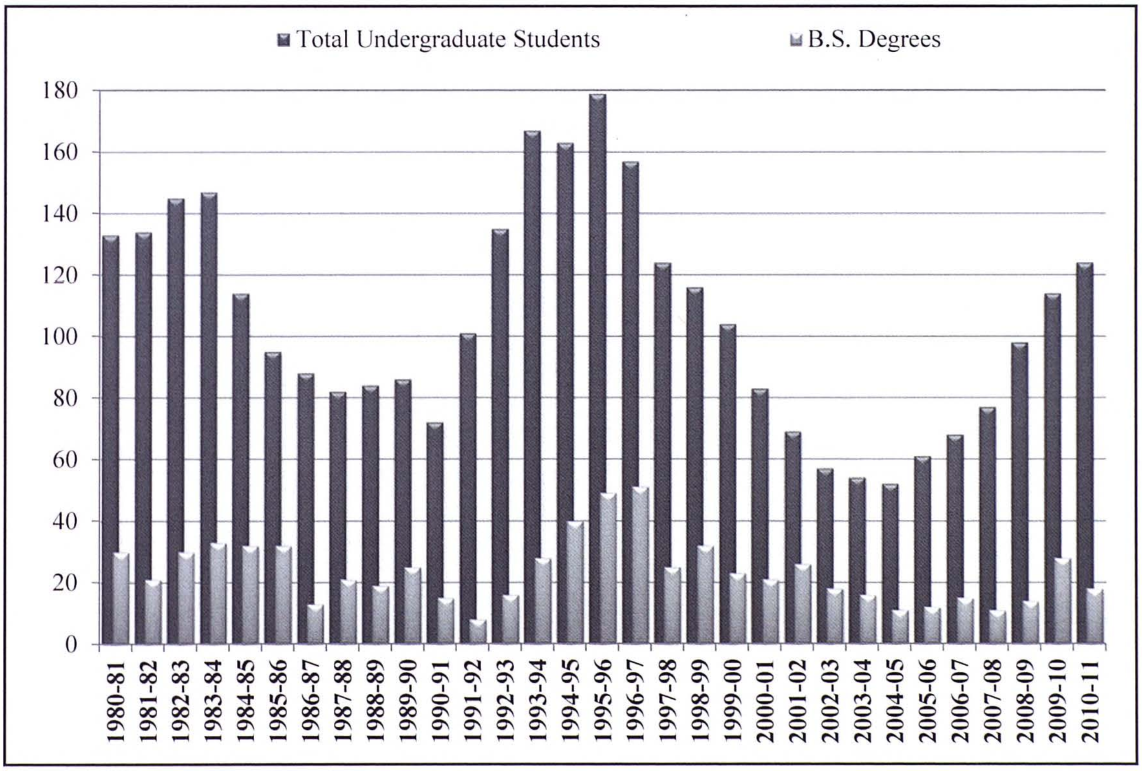


Figure 1. *Trends in undergraduate student populations and graduation rates.*

of petroleum refineries, is still in use today. Under Nelson's leadership, the department became internationally recognized for its program, which emphasized petroleum refining. Professor **Paul Buthod**, who authored the heat transfer chapter in Nelson's refining book, served as department chair for 14 years and was responsible for maintaining and expanding the department's reputation in petroleum refining. Buthod was truly a legend at TU, winning numerous outstanding teacher awards. In 1967, the department was granted a Ph.D. program, and in 1968 Professor **Francis S. Manning** was brought in as chair to help develop the fledgling program. Soon, the department was graduating two to three Ph.D.'s every year because of the many gifted students who came to study.

Since that time, the department has maintained a strong undergraduate program suitable for careers in oil, gas, and energy, but also diversified particularly into alternative energy and environmental areas. Today, alums of the department hold positions in a diverse array of chemical engineering sectors.

Another important event, more in the recent history of the department, was the formation of the Industrial Advisory Board in 1979. This Board meets twice per year, and helps keep the department in touch with the practical aspects of chemical engineering. A listing of the current advisory board members is in Table 1.

TABLE I
Department of Chemical Engineering Industrial Advisory Board

Ken Agee, President Emerging Fuels Technology
Mark Agee, Investor and Consultant
J. David Iverson, Managing Director Kayne Anderson Capital Advisors
Dan Lansdown, Process Consultant Domain Engineering
Chris Mayfield, Process Engineer ONEOK Partners
Calvin C. McKee, President (retired) Warren Petroleum Company
Tom Russell, CEO Thomas Russell Co.
Tom Steiner, President Vaprecom, Inc.
W. Wayne Wilson, Senior Fellow Emeritus ConocoPhillips Company
Omar Barkat, Executive Director PetroProTech
Wayne Rumley, CEO R&R Engineering Co., Inc.
Rakesh (Rock) Gupta, Manager of Engineering Thermal Process Engineering, Inc.
Jim Beer, Sales Engineer Hartwell Environmental Corporation
Darla Coghill, Science Department Chair Will Rogers College High School, Tulsa, OK
Chris Collins, Senior Analyst CITGO Petroleum Corporation
Jon Edmondson, Business Planning Mgr - Alaska Shell Exploration & Production Company
Reed Melton, Vice President Thermal Process Engineering, Inc.
Derrick Oneal, Process Engineering Manager Thomas Russell Co.
Troy Reusser, Vice President Koch Methanol, L.L.C.
Sharon Robinson, Senior Vice President Copano Energy, L.L.C.

FACULTY

The department consists of nine full-time faculty members, and all have Ph.D.'s in chemical engineering. Ages, interests, and academic experience levels are diverse: The latest two joined in Fall of 2008, while the most senior arrived in 1968.

Selen Cremaschi, assistant professor, earned both her B.S. (1999) and M.S. (2001) degrees from Bogazici University (Turkey) and received her Ph.D. (2006) from Purdue University, all in chemical engineering. During her Ph.D. studies, she worked as a research assistant at the NASA Specialized Center of Research and Training in Advanced Life Support (ALS/NSCORT), and her work focused on developing novel algorithms for process synthesis and design optimization under uncertainty. Following her graduation, she served as a post-doctoral research associate and assistant research scientist in e-Enterprise Center of Discovery Park, Purdue University, before joining our department in 2008. Her research interests are in process synthesis, design, and optimization under uncertainty. Her research group works at the intersection of operations research and chemical engineering, and develops

Chemical Engineering faculty in Keplinger Hall. Left to right: Ty Johannes, Laura Ford, Geoffrey Price, Christi Patton Luks, Selen Cremaschi, Dan Crunkleton, Frank Manning, Keith Wisecarver, and Kerry Sublette.

systems analysis and decision support tools for complex systems, especially for the energy area. Cremaschi received a Tau Beta Pi Teaching Excellence award in 2010 and an NSF CAREER award in 2011.

Wellspring Assistant Professor **Tyler (Ty) Johannes** also came to the department in 2008. He brings biochemical engineering expertise to the department and his areas of research focus are synthetic biology, directed evolution, and bioenergy. Johannes holds a B.S. in chemical engineering (2002) from Oklahoma State University, and both an M.S. (2005) and Ph.D. (2008) in chemical engineering from the University of Illinois. His current work focuses on engineering microalgae for the production of natural products and biofuels. He is also a licensed professional engineer.

Associate Professor **Daniel Crunkleton** is an alumnus of the department, receiving his B.S. in 1995. After his undergraduate studies, he attended the University of Florida as a NASA Graduate Student Research Fellow, receiving his Ph.D. in 2002. Following a post-doctoral appointment at Vanderbilt University, Crunkleton joined our department in 2003. While serving as full-time faculty, he attended law school at the University of Tulsa, and obtained his J.D. in 2008. He is also a registered professional engineer, and is the director of the Alternative Energy Institute at the University of Tulsa. His areas of research interest are alternative energy, algae biofuels, and computational fluid dynamics.

Geoffrey Price, professor and department chair, joined the faculty as chairman in 2000. He holds a B.S. from Lamar University (1975) and Ph.D. from Rice University (1979), both degrees in chemical engineering. Prior to his appointment in his current capacity, he served on the chemical engineering faculty at Louisiana State University - Baton Rouge for more than 20 years, and is emeritus professor there. He is a Fellow of the AIChE and his research interests are in heterogeneous catalysis, particularly zeolite catalysis. Current work is focused on catalytic conversion processes applied to the production of biofuels.

Laura Ford, associate professor, joined our faculty in 1999, while completing her Ph.D. in chemical engineering at University of Illinois at Urbana-Champaign the same year, and where she also obtained an M.S. in 1997. Her undergraduate degree is from Oklahoma State University (1993). Her research is on the dry etching of metals and photovoltaic alloys, studying the kinetics of the etching reaction under low vacuum conditions. The effects of oxidant, temperature, total pressure, and surface treatment have been studied. Ford is also an investigator in the University of Tulsa Hydrates Flow Performance joint industry project, where she studies the remediation and prevention of hydrate plugs.

Christi Patton Luks began her academic career in the department in 1997 as senior lecturer. She now holds the position of applied associate professor. Luks has a B.S. in chemical engineering from Texas A&M University (1981), an M.S. in applied mathematics from the University of Tulsa (1988), and a Ph.D. in chemical engineering from the University of Tulsa in 1992. She studies innovations in chemical engineering pedagogy and effective ways to blend technology with learning. She has received numerous teaching awards at the University of Tulsa including the most prestigious, university-wide Outstanding Teacher Award. She works actively with Engineers Without Borders, Society of Women Engineers, American Society for Engineering Education, American Institute of Chemical Engineers, and numerous other organizations.

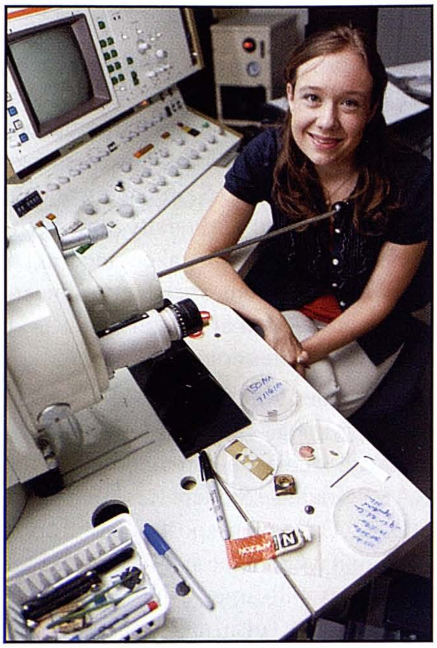
Professor **Keith Wisecarver** has expertise in the general area of multiphase reactor design and modeling, multiphase flows with reaction, and computer-aided process design, particularly as applied to petroleum refining and other energy processes. The main thrust of his current research is in the field of delayed coking, a petroleum refining process that uses high-temperature thermal cracking to convert the heaviest cuts of crude oil to lighter fractions such as gasoline, diesel, and gas oil, plus petroleum coke. He is co-principal investigator for the Tulsa University Delayed Coking Project (TUDCP), a research consortium of 19 energy-related companies. Wisecarver holds B.S. (1979), M.S. (1983), and Ph.D. (1987) degrees from Ohio State University. He is also a licensed professional engineer.

Kerry Sublette is the Sarkeys Endowed Professor of Environmental Engineering. In addition to his primary appointment in chemical engineering, Sublette also has a joint appointment in the Geosciences Department. He holds a B.S. in chemistry from the University of Arkansas, an M.S. in biochemistry from the University of Oklahoma (1974), and both an M.S.E. (1980) and Ph.D. (1985) in chemical engineering from the University of Tulsa. His research interests include bioremediation of petroleum hydrocarbons, restoration of soil ecosystems, ecological indicators of soil restoration, remediation and restoration of brine-impacted soil, and subsurface microbial ecology of groundwater impacted by hydrocarbons and chlorinated hydrocarbons. He has been a faculty member in the department since 1986.

The longest-serving member of the faculty is Frank Manning, mentioned previously. Manning came to the University of Tulsa in 1968 as department chair after a successful academic appointment at the Carnegie Institute of Technology (now Carnegie-Mellon) from 1959-68. Manning was born in Barbados, and studied in Canada at McGill University where he earned a B. Eng. degree in 1955. He also holds M.S.E (1957), A.M. (1957), and Ph.D. (1959) degrees from Princeton University. The AIME awarded him the R.W. Hunt silver medal for a Transactions of the Metallurgical Society paper in 1969. His current interests are in oilfield processing of crude oil, natural gas, produced water, and natural gas plants. He is currently revising his two books, *Oilfield Processing of Petroleum: Vol. I – Natural Gas* and *Vol. II – Crude Oil*, which have been well received by industry and adopted as

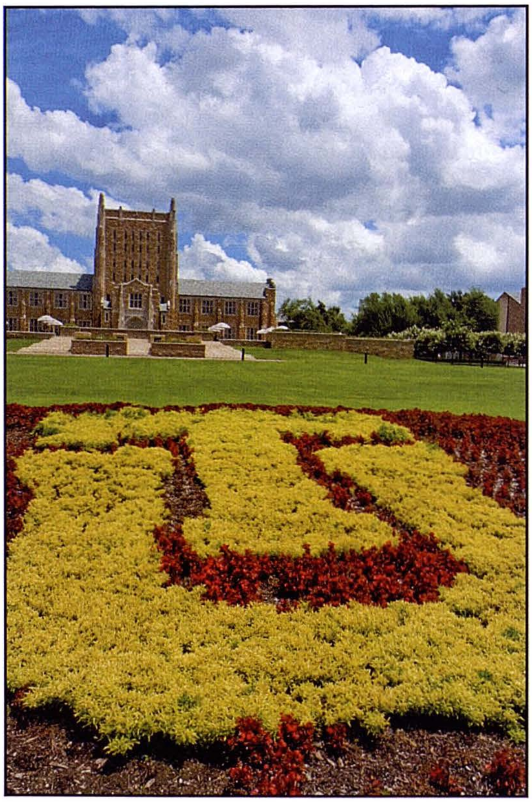
The TU experience . . .

Engineers Without Borders in Contani, Bolivia, installing a solar heating system. Left to right: ChE student Jasmine Htoon (the "T" in "TU"), ChE student Tsebaot Lemma, local professional and sponsor Jon Taber, ChE student Weston Kightlinger, Engineering Physics student Tim Brown, ChE student Sarah Edenfield, ChE faculty sponsor Christi Luks, and ChE student Philip Goree (the "U" in "TU").



Christina Bishop Jackson, Chemical Engineering Ph.D. student (now alumna) using a scanning electron microscope to study nanostructured battery electrolyte materials.

Congressman John Sullivan (in pink tie) visits the algae-to-fuels project in the Chemical Engineering Department. Left to right: Professor Geoffrey Price, Associate Professor Daniel Crunkleton, Sullivan, and congressional staffer Richard Hedgecock.



McFarlin Library on the University of Tulsa campus.

texts worldwide. Manning has won five teaching awards at TU and also the Outstanding Teaching Award from the Midwest Section of ASEE (1999). He is a professional engineer licensed in Oklahoma and Pennsylvania.

UNDERGRADUATE PROGRAM

The Educational Objectives adopted by the faculty of chemical engineering are:

> *"to provide a foundation for successful chemical engineering careers in the petroleum, natural gas, chemicals, alternative energy, environmental, materials, or biotechnology industries, and for graduate studies in chemical engineering or related fields such as medicine, law, and business administration."*

The curriculum has evolved over the years, but would be considered a traditional program for chemical engineers. Option programs (discussed in more detail below) allow students to specialize in areas of personal interest.

The B.S. curriculum is a minimum of 131 hours of total coursework and it is built upon the Tulsa Curriculum, which is required of every undergraduate student at the University of Tulsa. The Tulsa Curriculum requires all students to complete 6 hours in aesthetic inquiry and creative experience, 12 hours in historical and social interpretation, 7 hours in scientific investigation, and 6 hours of writing. Mathematics proficiency is also required by the Tulsa Curriculum.

Highlights of the chemical engineering program include emphasis in computer-aided design, which we base on HYSYS simulation software. The curriculum includes two courses in process control, two senior-level laboratory courses, and traditional instruction through a capstone plant-design course. In addition to many electives that students select to satisfy the Tulsa Curriculum, students choose two senior-level engineering electives, two upper-level advanced chemistry electives, an advanced math elective, and a senior-level advanced science elective. These elective courses can be used by students according to their individual interests, or students can choose an option program that focuses coursework in one of four areas.

Option Programs

In addition to a general option where students have the widest flexibility to choose elective courses according to their own interests, we offer options in:

- *Petroleum Refining*
- *Environmental Engineering*
- *Materials*
- *Pre-Med*

As of this writing, the chemical engineering faculty have approved a business option and we are awaiting approval from campus curriculum committees for this to become an official offering. Students completing the business option (assuming it is approved) will have all the background required for direct entry into the University of Tulsa's M.B.A. program without having to take any remedial courses.

Undergraduate Laboratory Facilities

In 2003, thanks to generous support by an alumnus, a faculty member, and the College, the department added a Honeywell Process Control system—originally based on Plantscape, but now upgraded to Experion process control software—to the unit operations laboratory. **Art Roslewski**, retired engineer from Honeywell Corporation, comes in part-time to help students and to design control algorithms and process diagrams that are similar to those used in industry. The lab was remodeled when the Honeywell system was added so that the process control system resides separately in a "control room." Existing experiments, such as fluid dynamics and heat transfer experiments, were integrated into the process control system where it was feasible, and new experiments have been added. In particular, the laboratory now sports a 6" diameter by 10' high packed absorption column made of glass so that students can observe the column dynamics and flooding phenomena, and a 3" diameter by 12' high continuous distillation column with 11 theoretical trays. Among the wide range of other experiments are those focusing on heat transfer, fluid mechanics, and process control.

In 1991, the Chemical Engineering Department was the first department at the University of Tulsa to have its own departmental personal computer laboratory. Four alumni provided the startup funding and requested that the lab be named after Paul Buthod, who is now an emeritus professor. Our advisory board, many of whom were students of Buthod's, helped design the lab and provided additional funding. Generous support from local industries and alumni helps keep the computing lab furnished with the latest computing hardware.

Study Abroad

The University of Tulsa has a very active study-abroad program, and chemical engineering students can take advantage of these programs. We accept transfer credit from international universities from dozens of countries given in numerous languages. Academic advisors help students choose courses and schedules that fit each student's needs and career goals. Currently, 15 - 20% of our students have participated in study abroad, and the percentages are growing rapidly.

Undergraduate Research/ TURC Program

The Tulsa Undergraduate Research Challenge (TURC) is a campus-wide program that enables undergraduates to conduct research with University of Tulsa faculty, and students in chemical engineering often take advantage of this program. Students, working with a faculty mentor, prepare a short proposal and submit it to the TURC program. The number of successful proposals varies from year to year, but the success rate is generally extremely high. Students receive financial support for supplies and for student wages through the TURC program to conduct original research work that can lead to publications. Overall, TURC scholars have brought prestige to the University of Tulsa by winning an incredible 104 nationally and internationally competitive scholarships, including Goldwater Scholarships, National Science Foundation Fellowships, Truman Scholarships, Department of Defense Fellowships, Udall Scholarships, Phi Kappa Phi Fellowships, Fulbright Scholarships, and British Marshall Scholarships.

TABLE 2

University of Tulsa AIChE Student Chapter ChemE Car History from 2000-2010

Date	Competition	Place	Award
Spring 2000	Mid-American Regional	St. Louis, MO	1st competition
Spring 2001	Mid-American Regional	Norman, OK	1st poster, 2nd competition
Spring 2002	Mid-American Regional	Iowa City, IA	1st poster, 3rd competition
Fall 2002	National	Indianapolis, IN	2nd poster
Spring 2003	Mid-American Regional	Lawrence, KS	3rd competition
Spring 2004	Mid-American Regional	Tulsa, OK	2nd competition, 2nd poster, most creative car
Fall 2004	National	Austin, TX	1st competition
Spring 2005	Mid-American Regional	Manhattan, KS	4th competition
Summer 2005	International	Glasgow, Scotland	1st competition
Fall 2005	National	Cincinnati, OH	2nd poster
Spring 2009	Mid-American Regional	Columbia, MO	3rd poster, most creative car
Spring 2010	Mid-American Regional	Ames, IA	2nd competition, 3rd poster

Student Organizations and Activities

The AIChE Student Chapter at the University of Tulsa has been very active and well organized for many years. Currently, Ty Johannes is the faculty advisor. AIChE generally sponsors annual trips to the AIChE Meeting and to the Midwest Regional student meeting. AIChE officers arrange for a speaker luncheon roughly every two weeks during the semester.

The AIChE ChemE Car Team has been one of the most successful teams in the nation, winning not only the national competition, but also the first international competition in 2005. The AIChE students also help sponsor an annual high school ChemE Car competition. A listing of the ChemE Car Team awards is given in Table 2.

A chapter of Omega Chi Epsilon, the chemical engineering honor society, was chartered at TU in April 2004. Christi Patton Luks is the faculty advisor. This group assists the department and college with recruiting and retention efforts. The chapter was responsible for the creation of ENS Ambassadors who give tours to college visitors. They also host study breaks during final exams and have helped build up a resource library for students in the Buthod Computer Lab.

Chemical engineering students are also active in other campus organizations including Tau Beta Pi, Society of Women Engineers (SWE), National Society of Black Engineers (NSBE), and American Chemical Society (ACS).

The University of Tulsa Student Chapter of Engineers Without Borders-USA (EWB) is advised by Luks and Ford. The chapter was started in 2006. EWB students have worked on several projects, including designing and building a kiln for a local Girl Scout camp and making water filtration pots from the Potters for Peace design. Recently, students and faculty advisors have been working in a village in the altiplano of Bolivia. With the Oklahoma East professional chapter, EWB has built eco-latrines (self-composting outhouses) for the village, which had fewer than five toilets of any kind when we started. The current project is designing a solar-heated shower and sink and an education program to encourage better handwashing in the community.

COMBINED BS/MS PROGRAM

Often called the 4/1 program, the combined Bachelor's-Master's degree program allows students to earn a B.S. and a Master of Engineering in chemical engineering (non-thesis master's degree) in five years. Students complete the regular coursework for the B.S. degree with the exception that some of the advanced engineering and science elective credit in the B.S. program are taken as graduate courses that are offered for outstanding students for undergraduate credit. These courses are then also counted as credit toward the Master's degree. Students in the combined B.S./M.E. program may either take a project course as part of the degree requirements, or pass the Master's comprehensive exam during their final semester of the combined program. The Master's comprehensive exam is a subset of the Ph.D. qualifying exam.

GRADUATE PROGRAM

The Department of Chemical Engineering at The University of Tulsa has offered a Master's degree program since 1939 and a Doctoral degree program since 1967. The department has a strong tradition in the energy and environmental fields, but has also diversified to offer research opportunities in materials engineering, biochemical engineering, advanced modeling and simulation, alternative energy, surface science, and catalysis.

Our current research focuses on modern experimental approaches and state-of-the-art computational studies. Our experimental approach to research allows investigation of fundamental phenomena as they are applied to "real world" problems, thereby enhancing our interactions with industry. Our computational studies address a wide range of complex problems in multiple time and length scales, ranging from multiphase flow models to complete energy supply chains, hence helping to catalyze solutions to complex societal challenges. Graduate study in chemical engineering at the University of Tulsa offers a dynamic environment for challenging and stimulating research, and at the same time provides a close interaction between faculty and students.

Curriculum and Unique Features

Students may begin any program in either the fall or spring semester. The four core classes required for all programs cover fluid mechanics, thermodynamics, reaction kinetics, and heat and mass transfer at an advanced level. Electives offered recently include surface science, petroleum microbiology, environmental engineering, petroleum refinery design, natural gas plant design, catalysis, biochemical engineering, combustion engineering, and advanced process optimization.

The Doctor of Philosophy degree provides students with an opportunity to reach a critical understanding of basic scientific and engineering principles underlying their field of interest, and to cultivate their ability to apply these principles creatively through advanced methods of analysis, research, and synthesis. The doctoral degree is awarded primarily on the basis of research. Each student selects a research topic and advisor during the first semester of the graduate program and, in consultation with the research advisor, forms an advisory committee. A Ph.D. qualifying exam must be completed satisfactorily. After completing the qualifying exam, the student must submit and defend a research proposal on the intended dissertation topic. After completion of the research activity, the student will write a dissertation on the results of the research, and defend the dissertation before the advisory committee.

The Master of Science degree is a research-oriented program that requires the completion of a Master's thesis and defense of the thesis in front of the advisory committee. Twenty-one hours of coursework (including 12 hours of chemical engineering core courses) and 9 credit hours of research are required for the completion of this program.

The Master of Engineering degree is a non-thesis professional degree that can usually be completed in 12 to 18 months. The Master of Engineering degree is a good option for students who do not have a chemical engineering undergraduate degree and students who are more interested in advanced coursework than in research work. Twenty-seven hours of coursework (including 12 hours of chemical engineering core courses) are required for this program, as well as a 3-hour master's project, supervised by a chemical engineering faculty member.

Students who have not earned a Baccalaureate degree in chemical engineering are usually required to complete a series of undergraduate-level chemical engineering courses before formal admission into the graduate program. The specific course requirements are determined based on the undergraduate coursework completed by the student, and decided on an individual basis.

Facilities

The Department of Chemical Engineering operates modern, fully equipped research laboratories with a wide range of specialized and unique experimental equipment. Keplinger Hall provides comfortable and modern laboratories and classrooms. Analytical instrumentation available within the department includes gas chromatography, GC-MS, high-pressure liquid chromatography, mass spectrometry, x-ray diffraction, microbalance, catalytic and non-catalytic reactor systems, high-vacuum surface science equipment, and numerous other pieces of equipment for experimental research. TU's Chemistry Department is also housed in Keplinger Hall, and this facilitates a close collaboration between the two departments, resulting in the availability of further sophisticated instruments including NMR, SEM, Raman, and LC-MS. State-of-the-art computer facilities including commercial process simulators are available in the Paul Buthod Chemical Engineering Computer Laboratory and in graduate computing laboratories.

North Campus Research Center

In addition to traditional laboratories described above, the University of Tulsa also has pilot plant scale facilities at a 10-acre site two miles north of the main campus known as North Campus. Of particular interest to chemical engineering at North Campus is a Special Projects building and Hydrates building. Chemical engineering faculty are involved in delayed coking, catalysis, and hydrates research using much larger scale equipment than is generally available on college campuses. The Hydrates project includes a 3 inch diameter, 160 ft long, 1500 psi flow loop, a 50 ft long clear pipe jumper facility, and a direct electric heating dissociation facility. The Special Projects building has about a 10,000 ft^2 footprint with 24-foot-high space indoors with full indoor climate control. Equipment that the Chemical Engineering Department houses in the building includes two one liter high-pressure stirred catalytic reactor systems and the Delayed Coking facility. The Delayed Coking facility includes a 2 gallon batch reactor, a 10 gallon coker for studying foaming from 850 to 950 °F, and a micro coker.

Tallgrass Prairie Ecological Research Station

The University of Tulsa and The Nature Conservancy (TNC) jointly operate The Tallgrass Prairie Ecological Research Station in the Tallgrass Prairie Preserve northwest of Tulsa. Equipped with laboratories, classrooms, library and computer facilities, and overnight housing, the research station supports a wide range of ecological research projects conducted by scientists and engineers from all over Oklahoma and the world who come to the Preserve to take advantage of this unique 40,000-acre living laboratory. TU's participation in the Research Station began through the Department of Chemical Engineering with a wide range of remediation projects related to oil and gas exploration and production on the Preserve. The need for a support facility within the Preserve was quickly apparent and a joint TU-TNC fund-raising campaign was launched that raised $2.4 million and saw the opening of the research station in 2004.

COMMUNITY OUTREACH

High School ChemE Car Competition

The department hosts a modified ChemE Car Competition for area high school students every spring. The high schoolers build a car powered by and stopped by a chemical reaction, and the competition is to see which team can get its car to stop the closest to a target distance announced just before the race. They may use commercial batteries and their cars do not carry a variable water load like in the AIChE national competition. The competition brings in an interesting mix of students, from 20 advanced placement chemistry students from a metro school to five students in basic chemistry at a rural school. The competition is intended as a recruiting tool for both chemical engineering as a profession and for the University of Tulsa, and some of the students have never been on a college campus before the event. The competition has been running for nine years with 89 teams total competing.[1]

Brownie Day

To promote science and engineering to the community, Luks brings 150 second- and third-grade Brownie Girl Scouts onto campus each semester for a day of math and science fun. With assistance from several departments, the students learn about science and engineering. The student AIChE chapter teaches the students about polymers through role playing where the students are assigned to be either a monomer or a cross-linker, then they make Gluep, a viscoelastic goo made from white glue and borax. The college students prod the girls to brainstorm engineering solutions to the manufacture of large batches of Gluep. The Brownies rotate through other hands-on activities where they learn the importance of designing a Lego™ bridge that is "on time, on budget, and on spec," visit a chemistry laboratory, experience statistics with M&M™ candies, and more. More than one young woman in our program today was first introduced to engineering at Brownie Day 10 years ago!

EXTRACURRICULAR

The University of Tulsa's Chemical Engineering faculty is a talented, dynamic group with a variety of research interests from biofuels and other alternative energy resources to directed evolution and zeolites. But this diverse bunch enjoys life outside the classroom just as much as they do inside:

- *Geoffrey Price and his sons are huge baseball fans, cheering for the Houston Astros and the LSU Tigers. Around Keplinger Hall, he's known for his extensive and colorful collection of neckties, most of which are provided by his wife who also is a Ph.D. chemical engineer.*
- *Frank Manning is in his office by 7:30 a.m. seven days a week (though he is sometimes "late" on Sundays) and enjoys following cricket worldwide, thanks to the Internet.*
- *Selen Cremaschi was a competitive ballroom dancer during graduate school. In fact, her husband was her dance partner before he became her life partner, and the two still hit the dance floor once a week at a local studio.*
- *Kerry Sublette cleans up nicely but is most at peace in a pair of jeans in the field working on his environmental projects.*
- *Dan Crunkleton apparently functions without sleep. The dedicated researcher is adjusting to life with a newborn baby at home and still manages to exercise every day.*
- *Christi Patton Luks is known as a scientist and mentor beyond Keplinger. A Girl Scout leader for 18 years, she also teaches a science class at her church and stirs up her own soap and cosmetics at home.*
- *Laura Ford is a Gregorian chant teacher and likes to commute to work by bike. Both activities may provide much-needed "recharging time" to Ford, who's busy raising five children with her husband who is a chemical engineer, too.*
- *Tyler Johannes maintains one of the neatest offices in the department and also kept order on the basketball court and baseball diamond, officiating games to help pay his way through college.*
- *Keith Wisecarver relishes foreign foods—Chinese, Japanese, Thai, and Indian—when he's out at a restaurant; but even when he's home, he cooks up a mean curry and can roll sushi like a pro.*

SUMMARY

Chemical Engineering at the University of Tulsa is a vibrant, accomplished group of students and faculty operating in concert for the educational benefit of students and the advancement of mankind through innovation, research, and ingenuity. The low student-to-faculty ratio fosters the close interaction of students and faculty, and excellent departmental and university resources add to the experience of all students. Best of all, the Chemical Engineering Department at the University of Tulsa is a close-knit community enjoying the university environment in an open and friendly manner.

ACKNOWLEDGMENTS

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1. Patton, C.L. and L.P. Ford, "Chemically Powered Toy Cars: A Way to Interest High School Students in a Chemical Engineering Career," *Proceedings* of the 2003 ASEE Annual Conference and Exposition, Nashville, TN ❒

Margot Vigeant

of Bucknell University

THERESA GAWLAS MEDOFF

There are some things that we ought to know—like that in a 70° F house, the floors are all the same temperature, regardless of whether they are carpeted or tiled—but somehow, we don't fully grasp the concept. Ask your average person, even an engineering student, and he or she will likely say that the tile floor is colder. That same engineering student could solve a math problem related to temperature, but that's not the same as fully understanding the concept. And when engineers make mistakes on fundamental concepts, it could lead to major problems.

Margot Vigeant in class, talking to a first-year student.

"It's really not good for a chemical engineer to be running around the plant thinking that different areas are somehow different temperatures just because the materials they are made of are better or worse heat conductors. We need to teach our students to translate their theoretical knowledge into conceptual knowledge," points out Margot Vigeant, whose current research focuses on assessing the prevalence and persistence of engineering students' misconceptions—and most importantly, finding ways to correct those misconceptions so that the lessons stick. She and Bucknell collaborators Mike Prince, professor of chemical engineering, and Katharyn Nottis, professor of education, have presented and published on this work, and they are working toward writing a packet of inquiry-based problems that could be used as a part of a chemical engineering workbook.

An associate professor of chemical engineering and associate dean of the College of Engineering at Bucknell University, Vigeant has spent much of her faculty career focusing on improving engineering education. Not only has she applied new teaching methods to her own courses, but she also has worked within the college and with colleagues at other colleges and has participated extensively in the American Society for Engineering Education (ASEE).

"Margot is well respected in the chemical engineering education community," says James Patrick Abulencia, assistant professor of chemical engineering at Manhattan College, who is

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Clad in plaid: Second-grader Margot smiles for the school camera.

Vigeant siblings Mark, Margot, Peter, Benjamin, and Fred at Peter's wedding. Can you guess which one is pursuing a sideline as a standup comic?

currently working with Vigeant on a National Science Foundation-funded project to use video to enhance conceptual learning in thermodynamics courses.

CREATIVE INFLUENCES

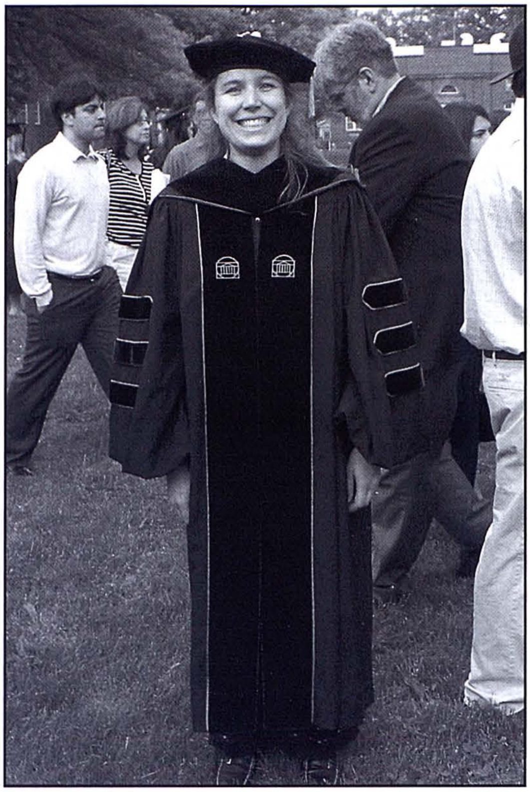
Perhaps Vigeant was destined to be an engineer—well, either that or an actress. She grew up in Stratford, Conn., the oldest of five children. The others were all boys. Theirs was a household in which engineering and other pursuits more traditionally thought of as creative were equally encouraged. Their father, Fred Vigeant, a chemical engineer by training, worked in marketing communications for Ciba-Geigy, which in 1996 became Ciba Specialty Chemicals. Their mother, Anita, was a caterer while the children were growing up, then went back to school and works as a nurse manager with the Visiting Nurse Association. "She is very hard working, and was always supportive of her children no matter what we were interested in, whether creative or technical," Vigeant says.

As she notes, the performance art line and the engineering line run through them all to greater or lesser extents. Vigeant has a great affinity for theater and literature, and she had considered being an English major in college. Even after she decided to pursue engineering as a discipline she remained involved in theater, performing in two Shakespearean plays while in college. The oldest of her four brothers works as the program director for an NPR station; another (who studied interactive technology at NYU) is an interaction and game designer; the third brother is breaking into improv theater in Chicago; and her youngest brother, Mark, just graduated from college with a degree in information science and is pursuing a career in that area as well as in banjo-unicycle-standup comedy.

Vigeant and several family members play musical instruments, and have been known to play together at nursing homes and other organizations during the holidays under the name the Vigeant Family Brass. She dons her orange-and-blue rugby shirt and her personalized orange-and-blue Chuck Taylor Converse All-Stars—a gift from her husband—to play the trumpet in the Pep Band at Bucknell basketball games.

As a child she would sometimes accompany her father to work, which she says was instrumental in pointing her in the direction of chemical engineering. "Chemical engineering is not something you can pretend to be as a child," she points out. "You can use Legos to play 'civil engineer' or kitchen ingredients to play 'chemist,' but there's no way you can play 'chemical engineer.' Half of the people in my undergrad ChemE class had a parent who was a chemical engineer. Otherwise they wouldn't have known about it as a career."

When Vigeant was a high school junior and senior, her father arranged for her to shadow several fellow employees at Ciba-Geigy to give her some career direction. "It seemed to me that chemists worked in the lab all the time," she says. "The chemical engineers got to move around to offices and different plants and work with a variety of people. The one female chemical engineer I shadowed took me to lunch in her beautiful red Corvette. It seems shallow now, of course, but that helped to sway me. It seemed like chemical engineers enjoyed a better life!" Vigeant—who drives a minivan, not a Corvette—still thinks she made the right career choice.



Grinning graduate Margot poses in her official University of Virginia regalia.

Margot among proud members of the Bucknell Pep Band playing at the Patriot League Basketball Championships, 2011.

FROM CORNELL TO UVA

Once she decided to pursue chemical engineering, it was a fairly easy choice to matriculate at engineering powerhouse Cornell University. She enjoyed her undergraduate experience there, particularly the extent to which she was able to take courses outside her major, an opportunity that was facilitated by the AP credits she had as well as by her willingness to work ahead with summer coursework to free up time and credits. "I received a really solid, rigorous chemical engineering education at Cornell, but I also took courses in French literature, psychology, acting, and as much biology as I could fit in." She was a teaching assistant in biochemistry as well.

As would be expected of Cornell College of Engineering, her chemical engineering curriculum was extremely challenging. "At least in our minds, my chemical engineering classmates and I were in the most difficult major in the most difficult college in this extremely difficult university, and we liked it that way," she recalls. "We didn't sleep much, and the extent to which we collaborated was based on the curve. There was definite competition among us."

Vigeant says she was particularly influenced by Dr. Michael Shuler, the James and Marsha McCormick Chair of the Department of Biomedical Engineering as well as the Samuel Eckert Professor of Chemical Engineering in the School of Chemical and Biomolecular Engineering at Cornell University. "When he talked about his research work in our Introduction to Chemical Engineering class, it was very inspiring," she says. At the time, back in 1990 or so, Shuler's research group was working on the drug Taxol (used to prevent reoccurrence of breast cancer) and the challenges of synthesizing and processing it. "One of the things you want to answer for yourself while an undergraduate is, what can I do with a chemical engineering degree, and seeing his research helped me to answer that," she says.

One of Shuler's graduate students, Susan Roberts, now director of the UMass Institute for Cellular Engineering, was also a big influence on Vigeant. "She helped me think through graduate school applications, and then was a critical resource again when I was applying for faculty positions. She's been an important professional mentor for me," Vigeant says.

When she was applying to graduate programs in chemical engineering, she had every intention of entering the pharmaceutical industry, which is one of the reasons she ended up at the School of Engineering and Applied Science at the University of Virginia. She was looking for a graduate school where she could delve into the biological aspects of chemical engineering, which is one of the major thrusts at the University of Virginia. Margot ended up working closely with Roseanne Ford, Cavaliers' Distinguished Teaching Professor and chair of the department of chemical engineering at UVA, who was indeed working on the biological aspects of chemical engineering, but from an environmental perspective, *not* pharmaceutical.

EARLY EXPERIENCE AS A RESEARCHER AND TEACHER

"Ford's project was just so compelling that I really wanted to work on it," Vigeant says. Ford and her team of graduate students and post-doctoral fellows (comprising chemical, mechanical, environmental, and civil engineers) in the Program for Interdisciplinary Research in Contaminant Hydrogeology (PIRCH) were researching the possibility of using contaminant-consuming bacteria to clean ground water polluted with gasoline components such as methyl tertiary butyl ether (MTBE) and trichlorethylene. The problem was getting the bacteria to go where the researchers wanted and to selectively seek and destroy the contaminants. Vigeant's research focused on individual bacterium and how bacteria move through the water's surface.

Research director Ford says, "Margot's project advanced my research program into important new directions. Bacterial adhesion to surfaces is not well understood, particularly with respect to the initial attachment events. What little was understood had been inferred from macroscopic-scale experiments. Margot studied the behavior at a microscopic level to gain some insight into the mechanisms governing bacterial adhesion. The other interesting aspect to her project was that the bacteria were motile—actively swimming—so the techniques used to study the initial attachment events had to be noninvasive."

Ford says that of all her graduate students, Vigeant stands out for her creativity and being able to bring a unique perspective to the problems the research group was working on. "One thing about working with Margot is that it broadened my research program because she asked questions and suggested approaches that I would not have thought about. There was one measurement we had been trying to make for a long time, and we couldn't figure out an exact approach. Margot was at a conference and heard someone talking about something similar. She saw how their approach could be adapted for our use. She is particularly good at seeing connections between fields and she is willing to cross disciplinary boundaries," Ford adds. Margot ended up collaborating with a professor and a post-doctoral researcher at the University of Virginia School of Medicine and using their lab's laser, microscope, image analysis software, and a technique called total internal reflection aqueous fluorescence. In the medical school researchers use the technique to look at cell membranes in great detail; she used it to see how close to the surface the bacteria were swimming.

"Margot was one of the top students I've had in terms of all-around intellectual ability, her work in the lab, her teaching, and her outreach to the community. She was the complete package," Ford says. While in graduate school Vigeant was a teaching assistant in chemical engineering. Ford says that as a teacher, too, she demonstrated creativity. Ford recalls observing a few of the recitations that Margot led for the undergraduate Momentum and Heat Transfer course. "She sang a song [composed by Dr. Peter Harriott] about the Reynolds number to help the students remember how to distinguish between laminar and turbulent flow. She prepared a game of *Jeopardy* to help the students review and summarize major concepts from the course material. The questions were very clever and fun, but also accomplished the goal of testing the students' knowledge of basic concepts. Margot has a knack for explaining difficult concepts in very simple terms. This was one quality that the students really appreciated about her and commented on in the student evaluations."

Vigeant also volunteered regularly as a guest teacher of science at local Catholic schools with her graduate classmate Jenny McNay. They had amazing success in making high-level concepts understandable by even the youngest children. That experience continues to feed into her social outreach to this day, as she has personally presented to Girl Scout and Boy Scout troops and has involved her students in working with youth groups and science teachers as well.

VIGEANT'S AWARDS
Professional
Best Paper Educational Research and Methods division, Best Paper Program Interest Group IV, ASEE (2011)
Hutchison Medal award from The Institution of Chemical Engineers, with Michael Prince and Katharyn Nottis (2010)
ASEE National Chemical Engineering Division Ray W. Fahien Award for teaching effectiveness and educational scholarship (2009)
Bucknell Presidential Award for Teaching Excellence (2006-07)
Nominee, AAUW Emerging Scholar Award (2004)
Nominee, best division paper ASEE Freshman Programs Division (2003)
Graduate
Chemical Engineering Faculty Award for Excellence in Doctoral Study (1999)
AAUW Selected Professions Dissertation Fellowship (1998-99)
UVA SEAS Graduate Teaching Assistant Award (1997)
Dean's Fellow (1994-1997)
Undergraduate
Tau Beta Pi National Engineering Honor Society

LANDING THAT DREAM JOB

With doctorate almost in hand, it was time for Vigeant to begin the job search. She looked broadly, including the pharmaceutical industry, various colleges and universities, even the CIA. Then the offer came for her dream job: as a tenure-track assistant professor at Bucknell University. "I remember a friend of mine who had graduated the year before telling me that on university job interviews you should talk only about research, never about wanting to teach students," she recalls. "But it was important for me to be able to go on an interview and say, 'I am interested in teaching undergraduate students.' I wanted to be at a place where the teaching of undergraduates is valued, not just an obligation. Bucknell is one of a very few liberal arts, undergraduate-focused, educationally focused schools with a chemical engineering major."

She began teaching at Bucknell in the fall of 1999. Early on in her career, Vigeant gave an talk titled "Teaching at a Four-Year College: Why Would Anyone Do This?" to her former colleagues in the PIRCH Seminar Series at the University of Virginia. She espouses the same feelings today about teaching that she expressed then: "It's all about changing the world. I really think that engineers have an opportunity to make the world a better place. Consider the story of penicillin. It was chemical engineers who found a way to deliver on the drug's promise by finding a way to mass produce penicillin and make it easily accessible. I could have helped to educate lots of other people and send them out there to change the world. You can multiply your effectiveness that way." After just 12 years of teaching Bucknell undergraduates, she figures that she has helped to train some 300 chemical engineers.

Margot, husband Steve, and sons Gabriel and Simon at Star Wars Celebration V, on the Millennium Falcon.

While that's the overarching motivation for teaching undergraduates, she points to many other rewards as well. "It's fun to try and get people excited about something you're excited about," she says, "and I derive great satisfaction from watching light bulbs turn on. Teaching is also a great way to learn. Students ask me something that causes me to figure out a problem I hadn't considered before, and when I'm teaching a new course I get to do lots of reading in new areas."

A FAMILY OF HER OWN

Vigeant was lucky enough to find the love of her life early on—very early on. She married her high school sweetheart, Steve Stumbris, in 1996 while still in graduate school. Stumbris also earned a bachelor's from Cornell, where he majored in mechanical engineering. He, too, is a theater lover who performed in student-led plays at Cornell. Both enjoy attending performances at Bucknell, which is known for its theater and dance programs. His career took a different direction from hers, and he worked as an engineer in various industry settings until a few years ago, when he joined the Bucknell University Small Business Development Center, where he is in charge of Engineering Development Services. Bucknell's SBDC is the only one Stumbris knows of that helps clients with product development, often with the assistance of the research of engineering students. "It was a wonderful alignment of our careers for us both to be at Bucknell," he says.

The couple has two sons, Gabriel, 10, and Simon, 7. As would be expected, their lives are busy with work, family, and children's activities such as scouting, soccer, and indoor rock-climbing (an activity to which Gabriel, particularly, has taken a liking). They wake at six every weekday morning, get the boys on the school bus by seven, and are in their offices before eight. Then it's full steam ahead until bedtime.

Weekends are devoted to family as much as possible, but even on their very busy weekdays Margot always finds the time to stop and listen and teach the children. Says Stumbris: "We often read ingredient lists with the kids. Just this morning over oatmeal Simon was reading the ingredients in his gummy vitamins and he was amused to see that they contained metal. That comment got Margot going on a 10-minute discussion about the function of iron in transporting oxygen in the bloodstream—and we still made it to their bus on time.

"Margot is always curious and enthusiastic. She might read or hear about a topic with the boys and they'll go off and research together to learn more about it."

Students and faculty from Engineering in the Global and Societal Context 2010: Brazil on top of Sugar Loaf, overlooking Rio de Janeiro (Margot, far right).

BRINGING A CREATIVE FLAIR TO ENGINEERING EDUCATION

Vigeant brings that same intellectual curiosity to the classroom, which inspires a similar attitude in her students. Recognizing that thermodynamics is an intensely challenging mathematical subject, she livens up her "quests" (something that falls between a quiz and a test) by using them to tell a story throughout the semester. She has used the story of Tristan and Isolde, and the Greek myth about the quest for the Golden Fleece, which has the added benefit of actually having mechanical monsters already built into the story. Last year's senior chemical engineering class playfully presented her with a golden-edged certificate for being "Most Likely to Slay a Dragon Using the Rankine Cycle."

"Dr. Vigeant was one of the most charismatic, energetic professors that I had. She was always in a great mood and tried to make any subject interesting, even thermodynamics," says David Van Wagener, '06, who went on to earn a doctorate in chemical engineering from The University of Texas at Austin. He now works as an associate engineer in the field of Sustainability Technologies at ConocoPhillips in Bartlesville, Okla.

She incorporates problem-based learning into her courses whenever possible. She rarely lectures to her Applied Food Science and Engineering students, for example. Instead, throughout the semester she presents them with a series of challenges, such as, "Is it possible to make a good doughnut that can be advertised as 'baked, not fried'?" The students start by frying doughnuts in class to see what sort of taste and consistency to aim for, and then begin innovating recipes and alternative cooking methods like steaming, baking, and cooking the dough in a panini-type press. While all that is going on, she passes around bags of baked and kettle-cooked "potato chips" for the students to taste and compare. They, too, are encouraged to look at the ingredients, where they learn that the baked chips are made to a significant extent of corn, not potatoes.

She uses that same investigative approach in the Bucknell engineering course designed for upper-class arts and sciences majors. When the innovator of that course retired, Vigeant had the opportunity to re-imagine its contents and methods. She changed the name, from "Technical and Critical Analysis" to "Life, the Universe, and Engineering." When she teaches the course, she works with students at the start of the class to set the agenda for which technologies (*e.g.*, cell phones, mp3 players, massive skyscrapers) and systems (*e.g.*, the Internet, genetic engineering, air pollution regulation) the class will study that semester. When possible, they actively answer the question "How Does It Work?" They might collect old cell phones, for example, and then smash them open to see the inner workings. They also discuss the social implications of the technologies or systems. The course is very popular at Bucknell, unfailingly enrolling to its target capacity of 16 students.

REVAMPING ENGINEERING AT BUCKNELL

Before Vigeant joined the faculty at Bucknell, there already was a concerted effort in place to revamp the curriculum to make it more student-centered and give students real-life challenges to solve instead of textbook-based problems. Soon after she arrived, she was enlisted to join fellow engineering faculty members on Project Catalyst, an NSF-funded, internal effort to "Engineer Engineering Education" at Bucknell. From that effort sprang the complete overhaul of both the first and the final courses that all Bucknell engineering students are required to take: Exploring Engineering and Senior Design.

Although not mandatory, many faculty redesigned their other courses as well. "We got the College of Engineering talking about ideas, reading books, listening to speakers, and developing new strategies for how to implement new methods of teaching," she says.

"Margot took a number of leadership roles in advancing the curriculum both within the Department of Chemical Engineering and in the College of Engineering as a whole," notes Jeff Csernica, professor of chemical engineering and chair of the Department of Chemical Engineering at Bucknell. He praises her "tireless work" on the various committees and subcommittees charged with broadening and improving the engineering curriculum. "She serves as a role model, not only to our women engineering students, but also to other faculty in terms of the vitality, creativity, and professionalism that she brings to her work," he adds.

Taking one for the team: Margot getting hit by a water balloon during the first-year "Douse the Deans" water balloon catapult-building event.

Vigeant is quick to point out that colleagues have been instrumental in getting her into the practice and scholarship of teaching engineering. In particular, she points to Bucknell chemical engineering colleagues Mike Prince, Mike Hanyak, and Bill Snyder.

Bucknell is working to make engineering education more global, and Vigeant has been an ardent supporter as well. In June 2010 she and colleagues Felipe Perrone, professor of computer science, and Tim Raymond, professor of chemical engineering, accompanied a group of 25 students from various engineering disciplines to Brazil for an intensive, three-week course, Engineering in the Global and Societal Context, that looks at engineering (education, businesses, projects) in another country within the context of that nation's culture and history. In June 2012 she will be going to China with another group of Bucknell engineering students and colleagues Xiannong Meng, professor of computer science, Jie Lin, professor of electrical engineering, and Keith Buffinton, dean of engineering.

EDUCATING FROM FIRST YEAR TO SENIOR YEAR

Recognizing that it is important to grab the attention of students early to keep them interested and engaged in engineering, Vigeant took on a leadership role in the redesign of the first-year seminar Exploring Engineering. She also served as coordinator of the course for three years. The course begins with a brief introduction to different types of engineering majors at Bucknell: biomedical, chemical, civil and environmental, computer science, electrical, and mechanical engineering. Then, students select three, three-week engineering challenges to complete with their classmates. One that she devised, which is still among the offerings, was "Engineering Athletics," a challenge to engineer a "better" (as defined by the students themselves) sneaker sole.

Vigeant's biggest contribution to the Exploring Engineering course was the final challenge of the semester, required of all 200-plus students enrolled in the course's multiple seminar groups. She wanted to make the project not only an engineering endeavor but also a College of Engineering-wide community service project. "Margot is one of the most energetic, passionate, and dedicated people I know," says Karen Marosi, associate dean of engineering at Bucknell University. "She's also incredibly creative, and when she gets a good idea, she'll go after it no matter what the barriers. Somehow she always finds a way."

The course's culminating challenge has changed over the years to keep it interesting and relevant. At first, students were asked to inventory the Bucknell campus and engineer solutions to make it more accessible to people with disabilities. When that subject became exhausted after several years, they did the same for businesses in the college's town of Lewisburg. Since 2006, the students, in groups of four, have been challenged to design and execute a "gizmo" that can be used to teach children a science or engineering concept such as the conservation of energy. Their real-life customers are local teachers and students, home-schooling families, and youth groups like the Boy Scout and Girls Scouts who attend the College's much-anticipated Gizmo Expo each December.

"There's a lot of learning that goes on when students have to convert a paper plan to implementation," Vigeant says. "They have to define what problem they are trying to solve, pick

Last year's senior ChE class playfully presented her with a golden-edged certificate for being "Most Likely to Slay a Dragon Using the Rankine Cycle."

the best solution, defend their choice, respond to customer feedback, build the gizmo—and make it work!" The initial, consulting customers for the gizmos are education students in Bucknell's Teaching Elementary Science course, taught by Lori Smolleck, associate professor of education.

The final step for the student groups is demonstrating the products at the Gizmo Expo. If any of the adults at the Expo request the gizmo, the students have to give it away. "It's our community service," she explains. "I wanted to find a way to motivate the students' projects, to show that there is someone out there who cares about this besides us and for reasons other than a grade."

Vigeant has presented and published numerous times on the first-year course at Bucknell, and particularly the gizmo project that she designed.

The final engineering course that Bucknell students take, Senior Design, got the same kind of overhaul in a project lead by Jim Maneval, professor of chemical engineering. Rather than the final product being a design on paper, the course now culminates with an actual deliverable to a real client, either on- or off-campus. Margot's chemical engineering students frequently work with businesses that come to Bucknell's SBDC. Last year, for example, one group worked with the owner of a natural soap company, Pompeii Street Soap Co., to create an all-natural, detergent-free, liquid hand soap. It was not easy. Turns out, natural ingredients will foam fairly easily, but the customer/company owner did not want a foaming soap. The students did eventually succeed; top-secret formulation and product development is ongoing.

BEYOND ENGINEERING EDUCATION

Vigeant considers herself first and foremost a teacher, but she also conducts chemical engineering research unrelated to education (though she typically involves her students in that research). Since leaving UVA, she has continued her research into bacterial adhesion but took it in a new direction to study how E. coli flagella move. To do so, she worked with colleagues to build for Bucknell a total internal reflection aqueous fluorescent microscope.

She has collaborated with Ewan McNay, assistant professor of behavioral neuroscience at The University of Albany (SUNY), on their research measuring *in vivo* neurochemistry with microdialysis by creating a mathematical model of the brain-probe environment. The tool created by her and student Damon Vinciguerra has confirmed that the underlying assumptions being made by the neuroscientists were valid, and has provided new insight into the parameters that affect microdialysis measurements. "Without this tool, we had no way of knowing whether the data we were getting out was accurate. Margot's work has general applicability to all microdialysis studies," McNay says. "Working with Margot, I found her to be very responsive and highly knowledgeable, and she has excellent writing skills. I wish I had more colleagues like her." Others who have worked with her express similar sentiments, and she gets high praise on student evaluations as well. As Ford, her dissertation adviser, recognized early on, she is the complete package: a loving daughter, sister, wife, and mother; a scholar of the highest caliber; a creative thinker; a faculty member who serves her university in myriad ways; and a highly effective, committed teacher who is dedicated to advancing the scholarship of engineering education. ❐

Teaching

MASS TRANSFER AND FILTRATION USING CROSSFLOW REVERSE OSMOSIS AND NANOFILTRATION:

An Experiment for the Undergraduate Unit Operations Lab

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Water is a limited resource. Less than 1% of water on the planet is fresh and easily accessible, and it is projected that, by 2050, one-third of the global population will be without a secure source of clean drinking water.[1] These circumstances have prompted research into techniques that augment the amount of available fresh water through water reuse and desalination. Membrane separations have become a popular method of desalination due to recent advancements in the field coupled with the relatively low energy requirement compared to thermally driven desalination. With mass transfer, separations, and process engineering at the core of their curriculum, chemical engineers are uniquely suited to design optimized separation processes involving membranes if given the opportunity to learn about their operation. It is therefore imperative that we integrate membrane separations into the undergraduate chemical engineering (CHE) curriculum to prepare our students to tackle these grand challenges with new technologies.

In all ABET-accredited chemical engineering programs, a laboratory course is required to provide hands-on experience to students who have completed their core CHE coursework. Many CHE programs, including the Department of Chemical, Materials, and Biochemical Engineering (CMBE) at the University of Connecticut (UCONN), have been updating their laboratory curricula to more accurately represent modern technologies. The undergraduate CHE Laboratory at UCONN contains only two separations experiments: a pilot-scale double-effect evaporator and a 20-stage distillation column. These thermal separation methods have value as classical chemical engineering approaches. These techniques, however, are becoming obsolete in certain sectors of industry. Today's employers demand knowledge of newer separation methods from recent graduates. As membrane separations become more commonly employed, students require practical experience with a system that teaches key membrane separations concepts while reinforcing mass transport fundamentals. For this reason, a membrane separations experimental module

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was created for the CHE Laboratory course at UCONN. One component of this module is a crossflow reverse osmosis (RO) system.

Previously published studies on RO experimental development usually describe dead-end filtration systems.[2,3] These systems operate in a batch mode, using a pressure vessel to force water through the membrane. Dead-end filtration systems lack the ability to tightly control hydrodynamics, temperature, and water recovery, and are also subject to more serious concentration polarization. Other RO experiments employ commercial crossflow membrane modules.[4] It is often difficult and costly to change the membranes in these systems, however, limiting the variety of membranes that can be tested. The system described in this paper is a crossflow RO system designed to mimic the conditions of an industrial membrane module while permitting a wide array of controllable variables. This system allows the students to observe change in membrane performance with changing hydrodynamic and fluid characteristics.

This experiment seeks to introduce students to the vital membrane performance parameters: permeability and selectivity. Sometimes referred to collectively as permselectivity, these parameters are used to appropriately select a membrane for any particular separation challenge. Although this experiment focuses primarily on desalination, an understanding of these key performance metrics cuts across separation disciplines and applies to any liquid, gas, or biological separation.

During the experiment, students will calculate the hydraulic permeability and salt rejection of several commercial RO or nanofiltration (NF) membranes and compare their values to the manufacturer's specifications. This experiment is also designed to reinforce mass transfer boundary layer theory through an examination of concentration polarization (CP). Students will learn about the complex interplay between salt rejection, flux, and CP, and think critically about possible applications for each membrane, considering each one's permeability and selectivity. The students will be asked to defend their conclusions, forcing them to think critically about the key design factors in RO desalination (feed water quality, product water quality and quantity, and operating pressure/power requirement).

The system described in this paper was designed to be mobile, robust, and easy-to-use. Test cells were designed such that small, single-use membrane coupons can be changed quickly between tests to permit the evaluation of multiple types of membranes. Furthermore, given the length of an individual test, multiple cells in series were needed to ensure data reproducibility, permitting students to obtain three flux measurements for every pressure they test and expediting the generation of data. Due to the relatively short channel length, pressure drop across each cell is negligible. Finally, the system was mounted to a modified cart to allow demonstrations outside of the undergraduate laboratory. This system has been used for demonstrations to the Membrane Separations class at UCONN and to visiting high school students as part of UCONN's Exploring Engineering (E^2) summer program. While a cart-mounted system has this added benefit, it is not essential to the functionality of this system.

EXPERIMENTAL OVERVIEW

A diagram of the cart-mounted RO system layout is presented as Figure 1. Pre-cut, pre-wet commercial membrane coupons are sealed into each of the test cells, and the feed tank is filled with deionized (DI) or saline water. After a brief equilibration period (30 minutes) at high pressure, students measure permeate flow rate and conductivity. This process is repeated at multiple pressures for pure water and at multiple flow rates for saline water. Using this data, hydraulic permeability (A) and salt rejection (%R) are determined for each tested membrane. Boundary layer phenomena are also considered. The results are compared to the manufacturer's published specifications.

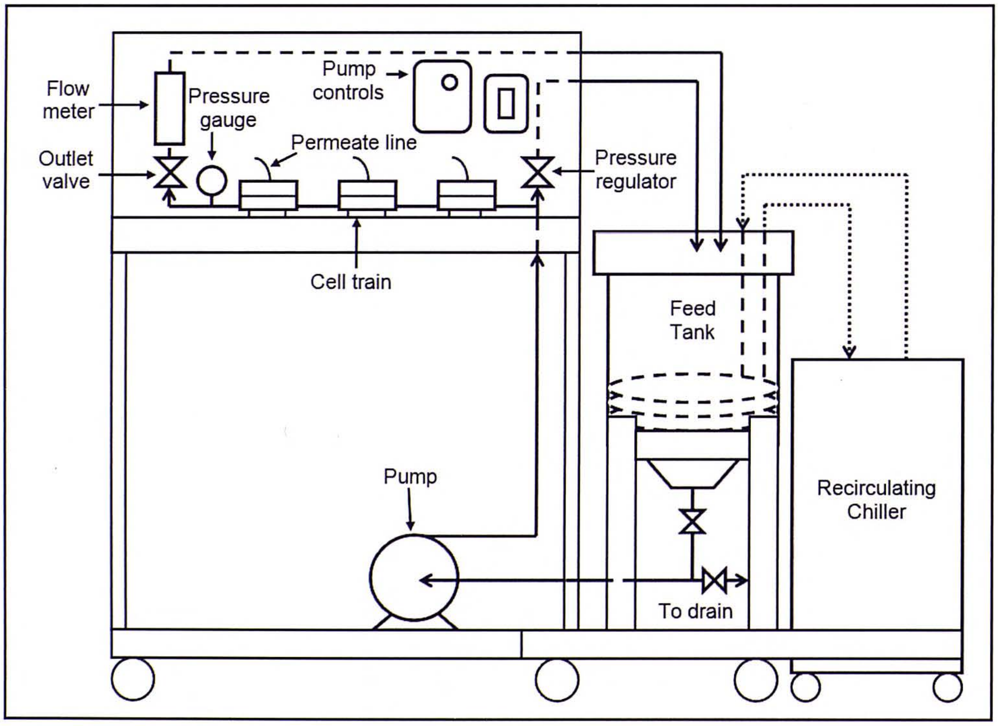
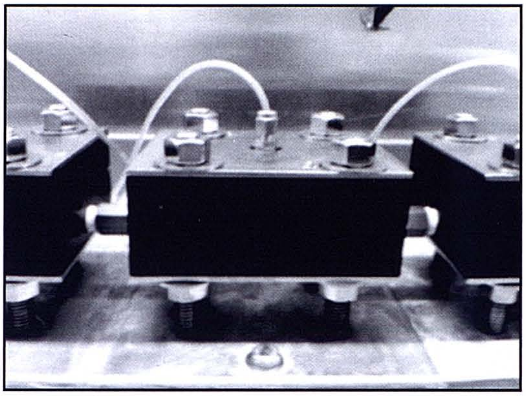
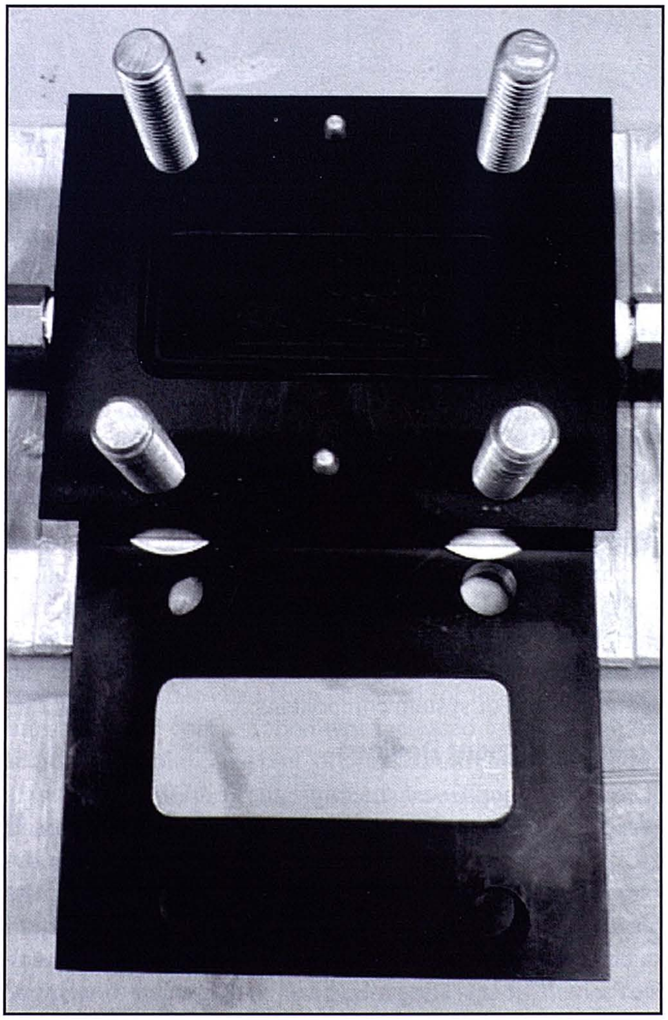


Figure 1. *Schematic flow diagram of the crossflow reverse osmosis system.*

Students are typically able to perform hydraulic permeability and salt rejection tests in approximately two hours for an NF membrane and three hours for a brackish water (BW) RO membrane. The length of this experiment can be extended by introducing more independent variables or different membranes. Prior to the experiment at UCONN, students read an instructional manual[5] and meet with a teaching assistant for system operation guidance. The RO system, as described, allows for control of many independent variables beyond membrane type and operating pressure, including crossflow rate, solute type, solute concentration, and temperature.



Figures 2. *Photographs of reverse osmosis test cell* ***(a, above)*** *when closed,* ***(b, below)*** *when opened. The open cell shows the feed channel (top) and the permeate collector (bottom). This permeate collector is a sintered stainless steel plate (Mott Corporation).*



REQUIRED EQUIPMENT

I. Membrane Selection

Flatsheet membranes have been graciously provided by Dow Water & Process Solutions for this experiment. Specifically, the BW30, NF90, and NF270 membranes were selected to provide students a wide range of membrane permselectivity.[6-9] Dow's seawater (SW) membranes could be used as well, but the low hydraulic permeability makes tests prohibitively long at the pressures tested with this system (up to 400 psi). RO membranes from other manufacturers are also appropriate. This experiment requires only small membrane coupons (approximately 8 in^2 per cell) that can be discarded after use.

II. Cell Design

The membrane cells are each composed of two halves fabricated from black delrin and supported with stainless steel plates. The bottom half contains a crossflow channel, with dimensions 3" long by 1" wide by 1/8" deep, fed via threaded ports drilled into the sides of each cell. Surrounding the channel is a Viton O-ring (3" OD, 1/8" thick, McMaster) seated in a groove, which serves to seal the cell and prevent leaking. The top of the cell houses permeate collector that prevents damage to the membrane at high pressure. This collector is made of sintered stainless steel from Mott Corporation (Farmington, CT). The collected permeate flows through a 1/8" threaded fitting inserted into the top of each cell. These fittings are connected to lengths of flexible PVC tubing for easy collection. The two halves are placed on threaded stainless steel rods that are mounted to a stainless steel base plate, which can easily be affixed to a cart. Washers and nuts are used to support and seal the cell. Photographs of a sample cell are included in Figures 2. Detailed cell schematics are available upon request. If fabrication facilities are unavailable, pre-made cells with a similar design can be purchased from Sterlitech, General Electric, or Separation Systems Technology.

III. Key System Components

The feed tank selected was a 5-gal Easy Drain cylindrical tank with stand from McMaster-Carr (Princeton, NJ). Reinforced PVC tubing joins the feed tank to the Multi-Speed Diaphragm Pump purchased from Wanner Engineering (Minneapolis, MN). A drain is installed in this line to facilitate system cleaning. The pump drive is equipped with a variable speed controller that regulates the pump diaphragm frequency. The variable speed pump permits tests in the RO, NF, and ultrafiltration (UF) pressure regimes (although only NF and RO regimes are tested during this experiment). A high-pressure

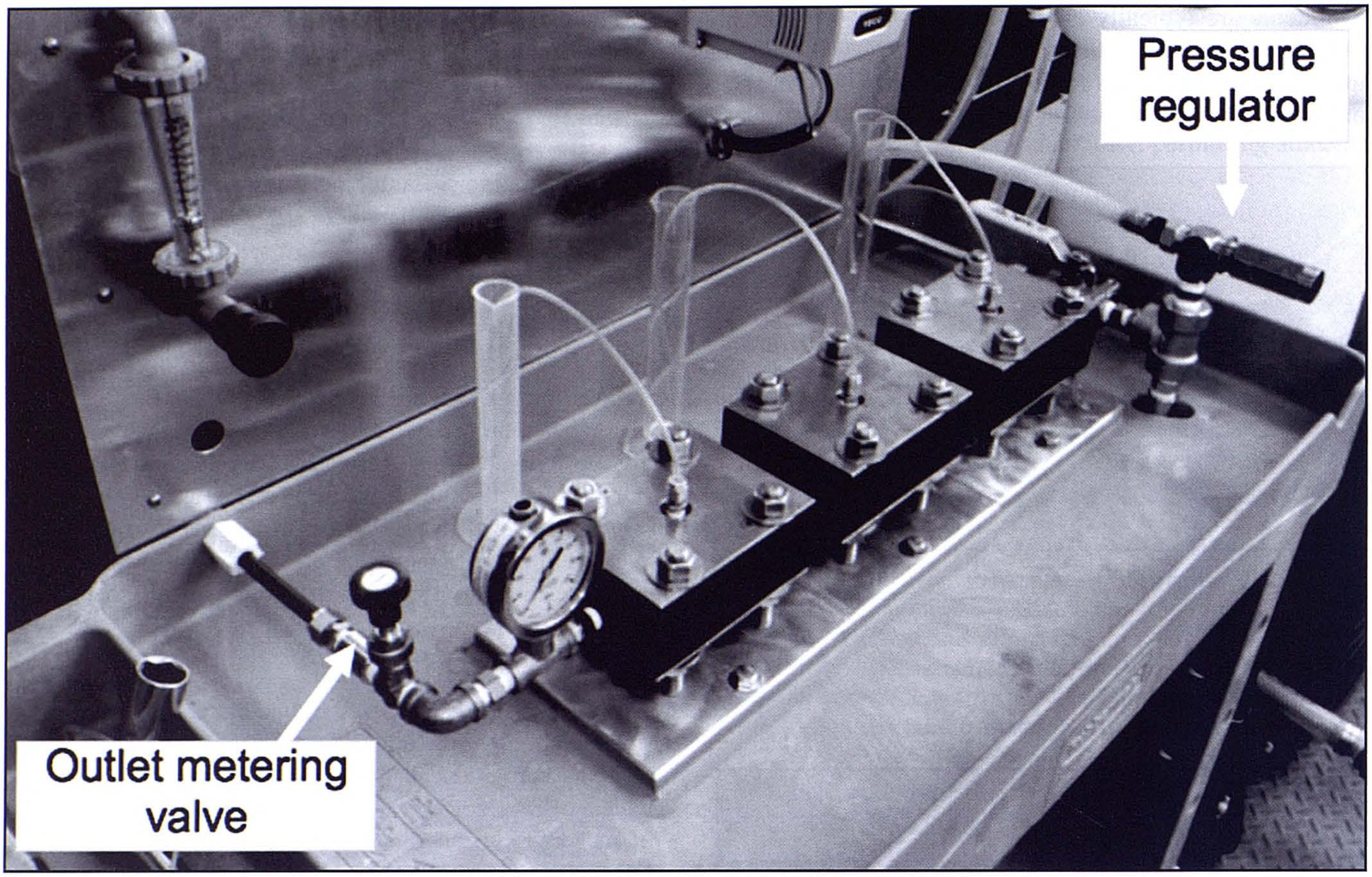


Figure 3. *Membrane cell train with bypass pressure regulator and outlet valve labeled.*

stainless steel braided hose (McMaster) connects the pump outlet to a stainless steel tee through the surface of the cart. This tee is connected to the first cell. System pressure and fluid flow rate are regulated by a pair of valves. The first is a front pressure regulator (50-500 psi, Wanner), which is installed on the aforementioned tee directly before the cell train and functions as a bypass valve. The second valve is a Swagelok SS-4L2 metering valve (Connecticut Valve and Fitting Co., Norwalk, CT), which regulates the flow of liquid that leaves the cell train. The effluent from this valve flows through a panel-mountable flow meter (0-1 gpm, McMaster). Liquid leaving the bypass regulator and flow meter are returned to the tank via tubing joined with quick-disconnect fittings to permit easy system flushing. A glycerin-filled pressure gauge (0-400 psi, McMaster) is installed between the membrane train and outlet valve. Figure 3 is a photograph of the membrane train with the two valves labeled. These valves are essential to optimal function of this system as they allow pressure and flow rate to be manipulated independently. An air purge port was also installed to allow the user to purge the system of residual water after cleaning. Filtered air is recommended to prevent oil or other particulates from contaminating the system. System temperature is maintained using a Neslab ThermoFlex 1400 recirculating chiller (Fisher) that has been integrated into the system through a coiled length of 316 stainless steel tubing that resides in the feed tank. The recirculator ensures temperature consistency by dissipating any heat generated by the pump during operation.

When selecting piping, tubing, and other fittings for the RO system, it is critical that all wetted parts resist corrosion, which could foul membranes or result in leaks. All pressurized components of the system (from the pump to the outlet valves and pressure regulator) should be plumbed using 316 stainless steel fittings and pipe. Any low-pressure areas may be plumbed using nylon or PVC fittings and hose. All major plumbing components (pipe, tubing, and fittings) were purchased from McMaster-Carr, unless otherwise specified. All components were mounted directly to a Rubbermaid cart (McMaster) that had been modified with an aluminum backsplash and angle iron tank stand. Table 1 describes the estimated cost of system components.

IV. Measurement Devices

Permeate is collected directly into 50 mL graduated cylinders (McMaster). The cylinders allow data to be recorded quickly and easily. A stopwatch is used to accurately measure the collection times. When a saline feed is used, the conductivity of the feed and permeate, which correlates to salt concentration, is measured using an Oakton Conductivity Probe (Fisher). The probe must be calibrated to measure concentration of the selected solute, which is accomplished by testing the conductivity of a serial dilution of a 2000 ppm stock solution of sodium chloride or other salt. A long-stemmed dial thermometer (McMaster) is inserted into the feed tank to monitor feed temperature.

EXPERIMENTAL PROCEDURE

Before an experiment, a membrane sheet was cut into coupons that can fit within the cell and completely cover the o-ring. Gloves were worn whenever membranes were handled so as to minimize damage. RO membranes shipped from Dow are coated with glycerin, which acts as a humectant to prevent drying. The membranes were stored in DI water for at least 24 hours to remove residual glycerin. For longer-term storage, membranes must be kept in a refrigerator to prevent bacterial growth. Two liters of 5-M sodium chloride stock solution were prepared for use as a salinity adjuster during the test. Since the system is pressurized, safety glasses were worn during operation.

To begin a test, the feed tank was filled with 6 L of DI water, although more water may be needed depending on system hold-up volume. While wearing gloves, students loaded membranes and sealed them into each cell with the selective layer facing downward toward the open channel. The chiller was set to 25 °C, in accordance to Dow's published test parameters. This set point may require modification to offset heat generated by the pump and ambient temperature. The pump was activated to purge air from the lines. After a few minutes, the system was pressurized by gradually closing the bypass regulator and outlet valve, alternating valves until the pressure is 300 psi. The system was equilibrated at this pressure for 30 minutes to flush air from the permeate tubes while compressing the membranes to provide uniform hydraulic resistance throughout the test. Longer equilibration times are acceptable but not practical within a laboratory period. After the equilibration period, permeate from each cell was collected in the graduated cylinders over a period of time at a desired pressure. Pressures between 100 and 300 psi are recommended, although students were encouraged to measure flux at the manufacturer's test conditions (70 psi for Dow's NF membranes, 225 psi for Dow's BW membranes). To optimize time spent in the laboratory, only 10 to 20 mL of permeate were collected per cell per pressure and all permeate was returned to the feed tank after volume was recorded. Once permeate flow rates had been observed for three to five pressures, the feed concentration was increased to 2000 ppm by adding stock solution (41 mL of 5-M sodium chloride stock for a 6-L DI water feed). Using stock solution is important since it rapidly mixes in water relative to the dissolution of solid salt. After a brief mixing period, pressure was maintained at the manufacturer's test specification while crossflow rate varied from 0.1 to 0.5 gpm. At each new flow condition, students should wait a few minutes for the fluid in the permeate line to flush out. A sufficient amount of permeate should then be collected in order to measure the conductivity accurately, but total permeate volume should be minimized so that the experiment does not take too long. Once permeate volume and collection time were recorded, permeate and feed solution conductivity were measured, and all permeate samples were returned to the feed. This procedure should be repeated for at least three flow rates. Measurements should be repeated if time allows. Typical testing conditions for experiments performed by students at UCONN are summarized in Table 2.

After gathering all desired data, the tank was drained and refilled with DI water. The bypass and outlet return lines were disconnected and placed in a sink or a bucket with the outlet valve and pressure regulator bypass opened fully. The pump was then set to sufficient speed such that the flow rate was above 0.5 gpm. The tank was refilled with DI water as needed until the effluent conductivity was below 10 microsiemens (μS). If DI water is in short supply, a pre-rinse using tap water may be performed before a polishing DI water rinse. Flushing usually requires approximately 2 gal of water. The system was then purged with filtered compressed air to remove residual water. The cells were opened and the membranes removed to be examined for defects. If another test was to be immediately done, new membrane coupons were inserted and the procedure was repeated.

TABLE 1
Estimated Cost of System Components

Component	Supplier	Approx. Cost
Recirculating chiller	Fisher Scientific	$3,000
Pump & controller	Wanner Engineering	$2,500
Three test cells	n/a	$1,500
Cart & tank	McMaster	$250
Meters & gauges	McMaster	$200
Valves	Swagelock, Wanner	$350
Tubing & piping	McMaster	$600
Conductivity probe	Fisher Scientific	$600
Total		**$9,000**

TABLE 2
Typical Operating Conditions for RO Experiments

Variable	Typical Value/Range
Temperature	25 °C
Initial feed volume	6 L DI water
High-pressure equilibration time	30 min
Feed concentration	0 ppm NaCl, 2000 ppm NaCl
Hydraulic pressure	0 – 300 psi
Hydraulic flow rate	0.1 – 0.5 L/min

Due to the system's versatility, there are numerous other independent variables for students to explore if time permits. For pure water or saline water, students can explore the impact of temperature on flux and salt rejection. Temperatures can range from 15 to 35 °C. For saline water tests, the effect of solute concentration and solute type on observed salt rejection and CP can be examined. Other recommended solutes include magnesium sulfate and calcium chloride. Crossflow rate can also be held constant during salt rejection tests, varying pressure to increase and decrease flux. Furthermore, other commercial membranes can be tested.

TYPICAL RESULTS AND DISCUSSION

The relevant variables that differentiate RO membranes are hydraulic permeability (A) and salt rejection (%R). Salt permeability coefficient (B) can be used instead of %R, although rejection is generally a more pragmatic performance metric. In order to facilitate student analysis, it can be assumed that the feed solution is dilute. Therefore, the feed is an ideal solution with density and viscosity equivalent to that of pure water. Solute diffusivity can be approximated using the Nernst-Haskell equation.[10] The solution properties do not change appreciably during the test since the system is run at 0% recovery (all permeate is returned to the feed tank) with a constant feed concentration. For a thorough overview of RO theory and calculations, refer to the textbooks of Mulder and Baker.[11,12]

Flux is determined by normalizing the measured volumetric flow rate of permeate by the surface area of the membrane. Flux is typically reported in gallons per square foot per day (gfd) or liters per square meter per hour (lmh). Once fluxes have been determined for each cell at a given pressure, students will average the three flux values and calculate the standard deviation. Using these average fluxes and standard deviations, pure water flux is plotted vs. operating pressure in accordance with the generalized flux equation below:

$$J_w = A\left(\Delta P - \Delta\pi\right) \tag{1}$$

where J_w is water flux, A is the hydraulic permeability constant, ΔP is the transmembrane hydraulic pressure, and $\Delta\pi$ is the transmembrane osmotic pressure. As permeate pressure is atmospheric, ΔP equals the gauge system operating pressure, and $\Delta\pi$ is zero for pure water feeds. Figure 4 presents a summary of pure water flux data gathered by several groups of students using this system, presented with linear trend lines and standard deviation error bars. Note that students should report the units of A—the slopes of these lines—in either gfd/psi or lmh/bar. This portion of the experimental analysis teaches students that, in general, NF membranes (NF270 and NF90) are more permeable than RO membranes (BW30).

TABLE 3
Experimentally Observed Hydraulic Permeability (A) and Manufacturer's Reported A Value Range

Membrane Name	Calculated A value, pure water (gfd/psi)	Calculated A range, salt water (gfd/psi)	Manufacturer's A range (gfd/psi)
NF270	0.82	0.82 – 1.02	0.45 – 0.72
NF90	0.43	0.44 – 0.52	0.36 – 0.58
BW30	0.18	0.17 – 0.19	0.12 – 0.13

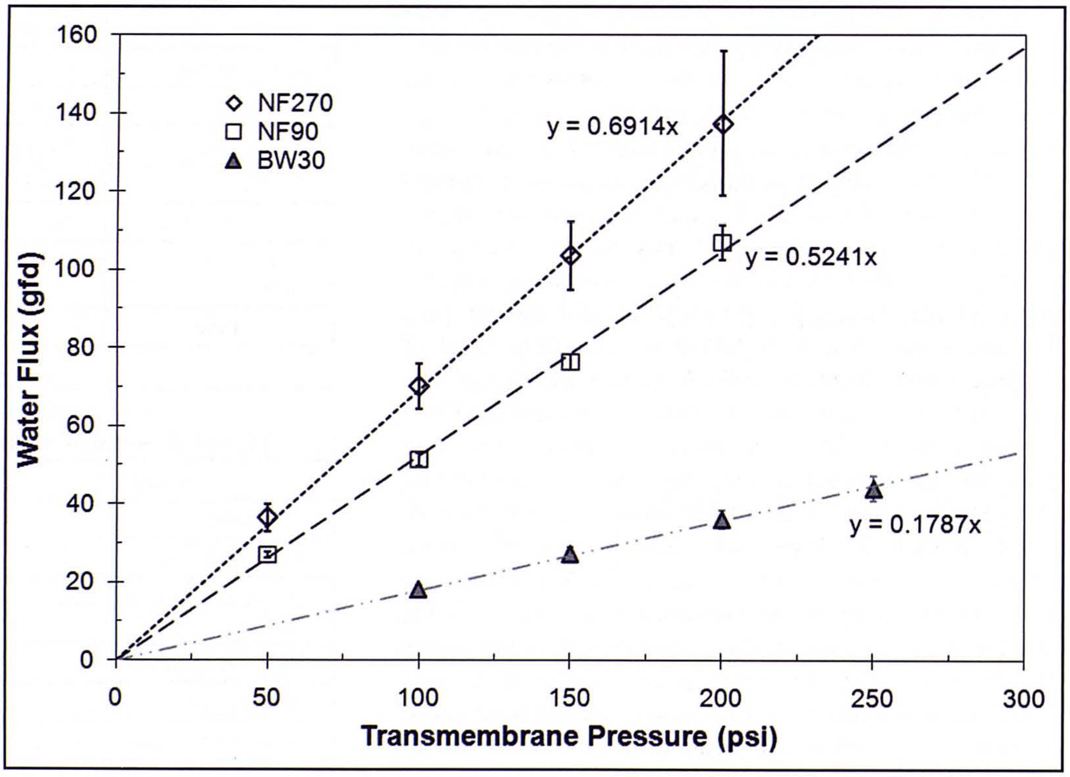


Figure 4. *Pure water flux vs. pressure for various NF and RO membranes from Dow Water & Process Solutions. Trend line slopes correspond to hydraulic permeability, A. Error bars indicate one standard deviation. Note that 1 gfd is approximately 1.7 l/m² hr.*

When a solute is present in the feed, the $\Delta\pi$ term in Eq. (1) is not zero. Furthermore, due to boundary layer effects, the osmotic pressure of the feed solution changes near the membrane interface. This phenomenon, illustrated in Figure 5, is known as concentration polarization (CP). Salts that are rejected by the membrane accumulate near the membrane surface while gradually diffusing back into the bulk solution. The relative rates of convection and diffusion dictate concentration of solute at the membrane interface. As a result, a steady state concentration gradient is established in which a bulk feed concentration, C_b, and a feed-side membrane interface concentration, C_m, are specified. For a thorough explanation of CP, refer to the review paper written by Sablani, et al.[13] A simple mass balance for flow of salt into and out of the boundary layer can be integrated into the following form:

$$\frac{C_m - C_p}{C_b - C_p} = \exp\left(\frac{J_w}{k}\right) \qquad (2)$$

where C_p is the concentration of solute in the permeate and k is the mass transfer coefficient which, according to film theory, is equal to molecular diffusivity divided by boundary layer thickness. The mass transfer coefficient can be determined using Sherwood number ($Sh = kd_h/D$) correlations available from a variety of sources.[10,14] The empirical Sherwood correlations presented to students in this experiment were provided by Mulder[11] for both laminar and turbulent flow in a channel, presented below:

$$Sh_{laminar} = 1.85\left(Re \cdot Sc \cdot d_h / L\right) \qquad (3)$$

$$Sh_{turbulent} = 0.04\left(Re^{0.75} \cdot Sc^{0.33}\right) \qquad (4)$$

where Re is the Reynolds number, Sc is the Schmidt number, d_h is the hydraulic diameter of the channel, and L is the channel length. For the flow rates mentioned previously, the system usually operates in transition flow, and the results of the two Sherwood correlations are averaged. Once C_m is known, CP modulus (C_m/C_b) can be reported; for RO, the CP modulus is always greater than 1. The osmotic pressures of the permeate solution, bulk feed solution, and feed solution at the membrane interface can now be calculated using the idealized van't Hoff equation, shown below:

$$\pi = iCRT \qquad (5)$$

where i is the moles of ions produced by the dissolution of one mole of the solute, C is the molar solute concentration, R is the gas constant, and T is the temperature. This equation, which indicates a linear relationship between concentration and osmotic pressure, is valid for dilute solutions. Thus, for relatively dilute solutions, the C_m, C_b, and C_p terms in Eq. (2) can be replaced with π_m, π_b, and π_p, the osmotic pressures of the solution at the feed-side membrane interface, bulk feed, and permeate, respectively.

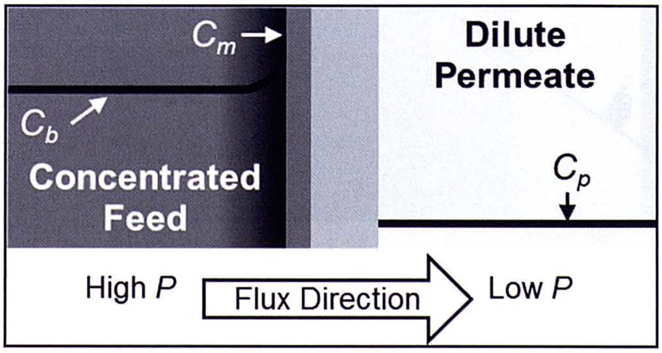


Figure 5. *Illustration of concentration polarization. The black line indicates the concentration of solute in solution.*

Membrane separations have become a popular method of desalination due to recent advancements in the field coupled with the relatively low energy requirement compared to thermally driven desalination.

During experimental analysis, students can be asked to ensure that the water permeability constant is the same for the pure water and saline feeds. To use Eq. (1), however, the students cannot use the observed osmotic pressure gradient ($\Delta\pi_{obs} = \pi_b - \pi_p$) to accurately evaluate A, as the term does not account for CP effects. Therefore, only the effective osmotic pressure gradient ($\Delta\pi_{eff} = \pi_m - \pi_p$) should be considered. When plotting flux vs. driving force (ΔP - $\Delta\pi_{eff}$), the data should be linear with a slope equal to the hydraulic permeability constant (A) and an x-intercept at zero, similar to the pure water test results. Table 3 compares A values calculated by one group of students based on pure water tests, saline water tests, and Dow's published performance values. Students should be able to observe that A values do not appreciably change in the presence of salt. Discrepancies can be attributed to minor performance differences between individual membrane coupons.

A more advanced analytical method is flux prediction, which combines Eqs. (1), (2), and (5) as follows:

$$J_w = A\left[\Delta P - \left(\pi_m - \pi_p\right)\right] \qquad \text{from Eq. } (1)$$

$$\pi_m - \pi_p = \left(\pi_b - \pi_p\right)\exp\left(\frac{J_w}{k}\right) \qquad \text{from Eq. } (2) \,\&\, (5)$$

$$J_w = A\left[\Delta P - \left(\pi_b - \pi_p\right)\exp\left(\frac{J_w}{k}\right)\right] \qquad (6)$$

Eq. (6), which is a nonlinear algebraic equation, can then be solved for water flux, J_w, using the experimentally observed feed concentration and hydraulic pressure along with the previously determined pure water permeability constant and mass transfer coefficient. Figure 6 is a parity plot of observed saline water feed flux data vs. water flux predicted by boundary layer theory at various crossflow rates and constant pressure. The film theory model fits the data well for these membranes. This portion of the analysis is an excellent demonstration of key aspects of boundary layer theory. If flow rate is varied during a saline water test, the mass transfer coefficient will increase with Reynolds number, resulting in a thinner boundary layer, lower CP modulus, and increased flux and rejection. If pressure is increased at constant crossflow rate, it is expected the boundary layer will grow as flux is increased and salt is forced against the membrane, increasing CP modulus and lowering observed salt rejection. The analysis also permits students to check the accuracy of their data against film theory and published data, forcing them to critically consider sources of error, such as erroneous assumptions, data misinterpretation, or poor data acquisition techniques.

The second key membrane performance metric is selectivity, often reported as observed percent salt rejection (%R) for RO. Rejection—the percentage of feed solute retained by the membrane—can be calculated using the following equation:

$$\%R = \left(1 - \frac{C_p}{C_b}\right) \times 100\% \qquad (7)$$

An additional means of quantifying selectivity is the calculation of intrinsic salt rejection ($\%R_{int}$), which accounts for concentration of solute at the membrane interface. This rejection value can be calculated as follows:

$$\%R_{int} = \left(1 - \frac{C_p}{C_m}\right) \times 100\% \qquad (8)$$

These rejections are compared to those published by Dow, accounting for the manufacturer's error limits, shown in Figure 7. The intrinsic rejection values are always greater than the observed rejection values, as the calculation accounts for CP effects and provides a more accurate measure of how much salt a membrane is capable of retaining. The observed rejection results are slightly lower than the published values, likely due to microscale defects that unavoidably form as membranes are shipped, cut, and loaded into the system. Minor defects may also form near the o-ring seals. The results, however, are within the limits of acceptable error as reported by Dow. This aspect of the experiment demonstrates the tradeoff between membrane permeability and selectivity. The most permeable membrane, the NF270, also has the poorest salt rejection. The inverse is true of the BW30, the least permeable membrane. Understanding this relationship is essential when selecting membranes for an RO process and is a critical aspect of understanding membrane separations.

All data presented in this manuscript were generated by senior-level chemical engineering students using the experimental apparatus as a part of the CHE laboratory curriculum. Students were expected to obtain accurate hydraulic perme-

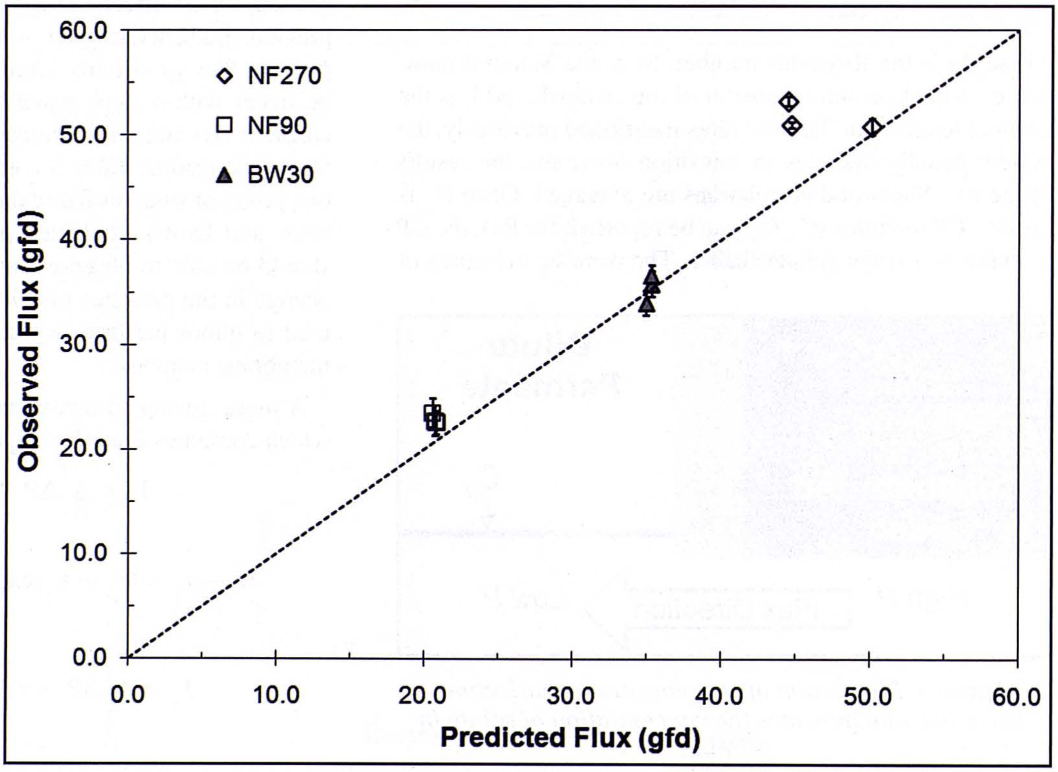


Figure 6. Parity plot of experimentally observed water flux and water flux predicted by film theory model with 2000 ppm NaCl feed at various crossflow rates. NF membranes evaluated at 70 psi, and BW membrane was evaluated at 225 psi. Error bars indicate one standard deviation. Note that 1 gfd is approximately 1.7 l/m² h.

ability constants and salt rejection values for each membrane while generating reasonable CP moduli. They were to observe the trade-off between selectivity and permeability and determine the impact of operating conditions, such as pressure and flow rate, on overall membrane performance. Based on written and oral lab reports, the majority of students who performed this experiment were able to meet these goals. Some of the first student groups to use the equipment cited cell leakage as a possible source of error. Placing thicker o-rings in the cells remedied this problem.

The versatility of this system has enabled its use outside of the unit operations laboratory. We have used this system to provide a brief introduction to membrane separations as part of UCONN's Exploring Engineering (E^2) Summer Program, which is aimed at teaching rising high school juniors and seniors about various facets of engineering. Using food coloring instead of sodium chloride in the feed, the system was used to introduce the students to basic membrane separations while teaching them the value of making assumptions (in this case, that osmotic pressure generated by the food coloring is negligible). Furthermore, this system has been successfully implemented as a demonstration in UCONN's Membrane Separations course for senior undergraduates and graduate students. The experiment was used to introduce students to more advanced aspects of RO, generating data from which students could calculate hydraulic permeability, salt rejection, and CP modulus.

CONCLUSIONS

This paper has described the design and use of a versatile reverse osmosis system that has been implemented in the chemical engineering senior laboratory capstone course at the University of Connecticut. Students learn the fundamental performance variables critical to membrane separations, namely permeability and solute rejection. Furthermore, the concentration polarization aspect of this experiment introduces students to a complex mass transport problem while reinforcing mass transport boundary layer theory.

Once students analyze their data and determine the permeability and rejection of the membranes, they must think critically about possible applications for each membrane they tested, based on each membrane's permeability and salt rejection. Students must consider vital parameters to the RO desalination process, such as feed water salinity, desired

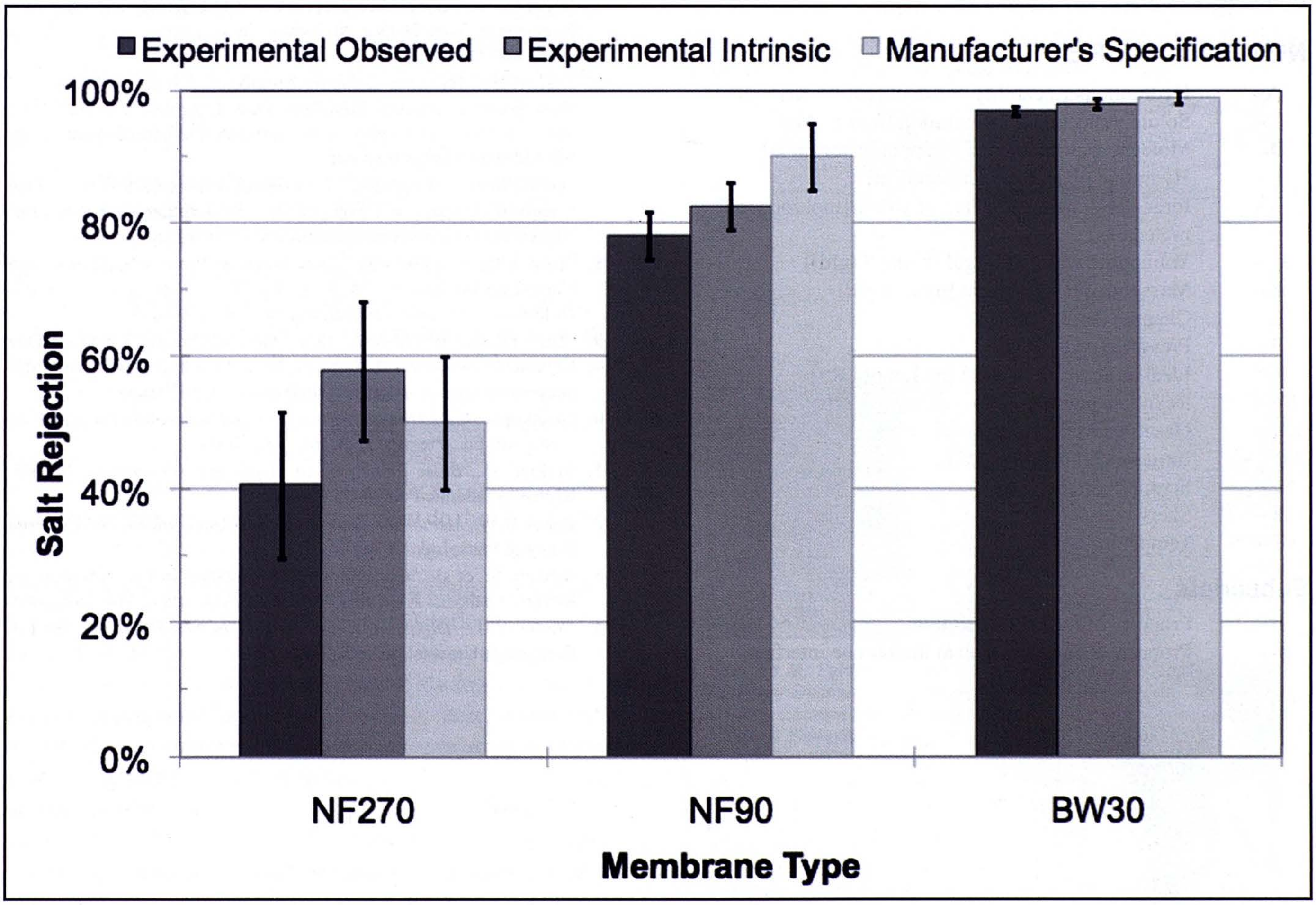


Figure 7. *Observed and intrinsic salt rejection of various membranes based on student observations and values reported by the manufacturer. Feed solution was 2000 ppm NaCl. Error bars indicate one standard deviation.*

permeate water quality and quantity, and operating power requirements and restrictions. While designed as an experiment for the undergraduate laboratory course, this portable system has curriculum-wide applications, such as providing demonstrations to freshman-through-graduate-level classes in addition to demonstrating a chemical engineering process to prospective students.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the Chemical, Materials, and Biomolecular Engineering Department at the University of Connecticut for providing the funds to build this experimental system. Additional funding was provided by the Robert and Beatrice Mastracchio Endowed Scholarship. The authors would also like to thank Dow Water & Process Solutions for generously donating the membranes used in this experiment. The data presented in this manuscript were gathered by Sean Andrew, Nathan Barlow, Emily Cole, Robert DeFilippe, Aleah Edwards, Kristina Gillick, Jonathan Goldman, Katherine Ivey, Timothy Largier, Philip Maiorano, Megan Nolan, Brendan O'Grady, Congtin Phan, Mark Williams, and Tracy Williams as part of the Chemical Engineering Laboratory course.

NOMENCLATURE

A –	Hydraulic permeability constant [gal ft^{-2} day^{-1} psi^{-1}]
C –	Solute molecular concentration [mol/L (M)]
D –	Molecular diffusivity of solute in water [m^2/s]
d_h –	Hydraulic diameter of channel [m]
i –	Ionic dissociation constant of solute [mol ions/mol molecules]
J_w –	Volumetric water flux [gal ft^{-2} day^{-1} (gfd)]
k –	Mass transfer coefficient [m/s, or gfd]
L –	Channel length [m]
P –	Pressure [psi]
R –	Ideal gas constant [1.205 psi L mol^{-1} K^{-1}]
Re –	Reynolds number
%R –	Observed salt rejection [%]
$\%R_{int}$ –	Intrinsic salt rejection [%]
Sc –	Schmidt number
Sh –	Sherwood number
T –	Temperature [K]

Subscripts

b –	Property of bulk feed solution
m –	Property of feed solution at membrane interface
p –	Property of bulk permeate solution
eff –	Effective conditions at the membrane interface
laminar –	Equation for laminar flow
turbulent –	Equation for turbulent flow

Greek

μ –	Fluid viscosity [kg m^{-1} s^{-1}]
π –	Osmotic pressure [psi]
ϱ –	Fluid density [kg/L]
υ –	Fluid crossflow velocity [m/s]
Δ –	Difference evaluated between feed and permeate conditions

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Random Thoughts . . .

LEARNING BY SOLVING SOLVED PROBLEMS

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See if this one sounds familiar. You work through an example in a lecture or tell the students to read it in their textbook, then assign a similar but not identical problem for homework. Many students act as though they never saw anything like it in their lives, and if pressed they will claim they never did. It is easy to conclude—as many faculty members do—that the students must be incompetent, lazy, or incapable of reading.

A few of our students may be guilty of those things, but something else is behind their apparent inability to do more than rote memorization of material in lectures and readings. The problem with lectures is that it's impossible for most people to learn much from a bad one, while if the lecturer is meticulous and communicates well, everything seems clear: the hard parts and easy parts look the same; each step seems to follow logically and inevitably from the previous one; and the students have no clue about the hard thinking required to work out the flawless derivation or solution going up on the board or projection screen. Only when they confront the need to do something similar on an assignment do they realize how much of what they saw in class they completely missed.

It's even worse when an instructor tells students to read the text, fantasizing that they will somehow understand all they read. There are two flaws in this scenario. Many technical texts were not written to make things clear to students as much as to impress potential faculty adopters with their rigor, so they are largely incomprehensible to the average student and are generally ignored. On the other hand, if a text was written with students in mind and presents things clearly and logically, we are back to the first scenario—the students read it like a novel, everything looks clear, and they fail to engage in the intellectual activity required for real understanding to occur.

A powerful alternative to traditional lectures and readings is to have students go through complete or partially worked-out derivations and examples in class, explaining them step-by-step to one another. One format for this technique is an active-learning structure called *Thinking-Aloud Pair Problem Solving*, or TAPPS.[1,2] It goes like this.

1. *Prepare a handout containing the derivation or solved problem to be analyzed and have the students pick up a copy when they come in to class. Tell them to form into pairs (if the class has an odd number of students, have one team of three) and designate one member of each pair as* A *and one as* B *(plus one as* C *in the trio).*
2. *When they've done that, tell them that initially* A *will be the* explainer *and* B *(and* C*) will be the* questioner(s).

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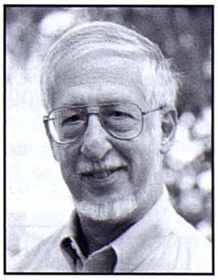

The explainers will explain a portion of the handout to the questioners, line-by-line, step-by-step, and the questioners will (a) ask questions *(if the explainers say anything incorrect or confusing), (b)* prompt the explainers to keep talking *(if they fall silent), and (c)* give hints *(if the explainers are stuck). If both members of a pair are stuck, they raise their hands and the instructor comes over and helps. The second function is based on the fact that vocalizing one's thinking about a problem sometimes leads to the solution.*

3. *The students first individually read the description of the formula or model to be derived or the statement of the problem to be solved; then the explainers explain it in detail to the questioners and the questioners ask questions, keep the explainers talking, and offer hints when necessary. Give the class 2–3 minutes for this activity.*
4. *Stop the students when the allotted time has elapsed, randomly call on several of them to answer questions about the description or problem statement they just went through, and call for volunteers if additional responses are desired. Add your own explanations and elaborations (you're still teaching here). Then have the pairs reverse roles and work through the first part of the derivation or problem solution in the same manner. When results are obtained that are not in the handout, write them on the board so everyone can see and copy them. Proceed in this alternating manner through the entire derivation or solution.*

After going through this exercise, the students *really* understand what they worked through because they explained it to each other, and if they had trouble with a tricky or conceptually difficult step they got clarification in minutes. Now when they tackle the homework they will have had practice and feedback on the hard parts, and the homework will go much more smoothly for most of them than it ever does after a traditional lecture.

Cognitive science provides an explanation for the effectiveness of this technique.[3,4] Experts have developed cognitive structures that enable them to classify problems in terms of the basic principles they involve and to quickly retrieve appropriate solution strategies, much the way expert chess players can quickly plan a sequence of moves when they encounter a particular type of position. Novices—like most of our students—don't have those structures, and so they have the heavy *cognitive load* of having to figure out how and where to start and what to do next after every single step. Faced with this burden, they frantically scour their lecture notes and texts for examples resembling the assigned problems and focus on superficial details of the solutions rather than trying to really understand them. They may learn how to solve nearly identical problems that way, but even moderate changes can stop them cold.

Sweller and Cooper[3] and Ambrose *et al.*[4] report studies showing that students are indeed better at solving new problems when they have first gone through worked-out examples in the manner described. When they have to explain a solution to a classmate, their cognitive load is dramatically reduced because they don't have to figure out every trivial detail in every step—most of the details are right there in front of them. Instead, they have to figure out *why* the steps are executed the way they are, which helps them understand the key features of the problem and the underlying principles. The effect is even greater if they are given contrasting problems that look similar but have underlying structural differences, such as a mechanics problem easily solved using Newton's laws and a similar one better approached using conservation of energy. Having to explain why the two problems were solved in different ways helps equip the students to transfer their learning to new problems.

Give it a try. Pick a tough worked-out derivation or solved problem, and instead of droning through it on PowerPoint slides, put it on a handout—perhaps leaving some gaps to be filled in by the students—and work through it as a TAPPS exercise. Before you do it for the first time, read Reference 2, note the common mistakes that reduce the effectiveness of active learning (such as making activities too long or calling for volunteers after each one), and avoid making them. After several such exercises, watch for positive changes in your students' performance on homework and tests and in their attitudes toward the class. Unless a whole lot of research is wrong, you will see them.

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Results of the 2010 Survey on

TEACHING CHEMICAL REACTION ENGINEERING

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The Chemical Reaction Engineering (CRE) course, while currently an essentially undisputed part of the core chemical engineering curriculum, is actually a fairly recent addition to the curriculum. A retrospective paper by Fogler and Cutlip[1] describes the introduction of the topic in the 1940s as one characterized by "gross approximations" for slide-rule calculations as part of broader process operations courses, while today it has developed into a dedicated, more computationally oriented course.

In 1957 the AIChE Education Projects committee began a series of surveys of the undergraduate curriculum as offered by chemical engineering departments in North America. These surveys continued under the auspices of the AIChE Special Projects committee until the late 1990s. In 2008, AIChE formed an Education Division which recognized the value of the survey for its characterization of how courses are taught at a broad range of institutions as well as for the opportunity to share innovative and effective teaching methods associated with specific courses. This paper presents the results for the second in the series of surveys conducted by the Education Division.

Much of the content of this paper was previously published as part of the American Society for Engineering Education 2011 conference proceedings.[2] This paper adds additional analysis and comparison with data from previous surveys.

SURVEY BACKGROUND

The Chemical Reaction Engineering course (CRE) is the topic of the 2010 survey. The aforementioned AIChE Education Projects committee previously conducted surveys on the same course in 1974,[3] 1984,[4] and 1991.[5] Other surveys on this course from that committee may exist but were not obtained by the authors. The current survey was designed in part to update the results published for those surveys.

The survey was conducted via Internet server hosted by the University of Kentucky running an open source software package, LimeSurvey (<*limesurvey.org*>). E-mail invitations to participate were initially sent to all department chairs in the United States and Canada requesting participation from the faculty members teaching the relevant course(s). A second

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request was sent to the instructors of record for the CRE course during the 2009-2010 academic year when that information was publicly available on the Internet. From that population of 158 programs, 62 usable surveys representing 60 institutions were received.

This 38% response rate represents an improvement from the results of the 2009 survey on the freshman introductory courses[6] (31%), but still falls short of the response rates in 1974 (58%) and 1984 (91%). No response data is available for the 1991 survey.

Responding programs represented great regional diversity and size, covering the United States and three Canadian provinces. Seventy percent of responding programs were from public institutions. The smallest responding department had an overall undergraduate chemical engineering enrollment of 37 students in 2010, while the largest had 730 undergraduates.[7] Median undergraduate program enrollment for responding institutions is 177.

The complete survey in print form is available in the ASEE Proceedings paper.[2]

COURSE TIMING

The most common timings for the course within a program's curriculum were at the end of the junior year or at the start of the senior year, with a slight edge to the junior-year start. The distribution of the timing of course offerings is given in Figure 1. Figure 2 offers a historical comparison of offerings by term, which indicates there has been a shift toward offering the first course in CRE to the junior year. In 1974, 13% of reporting programs taught the course in the junior year, and in 2010 that percentage is about 50%.

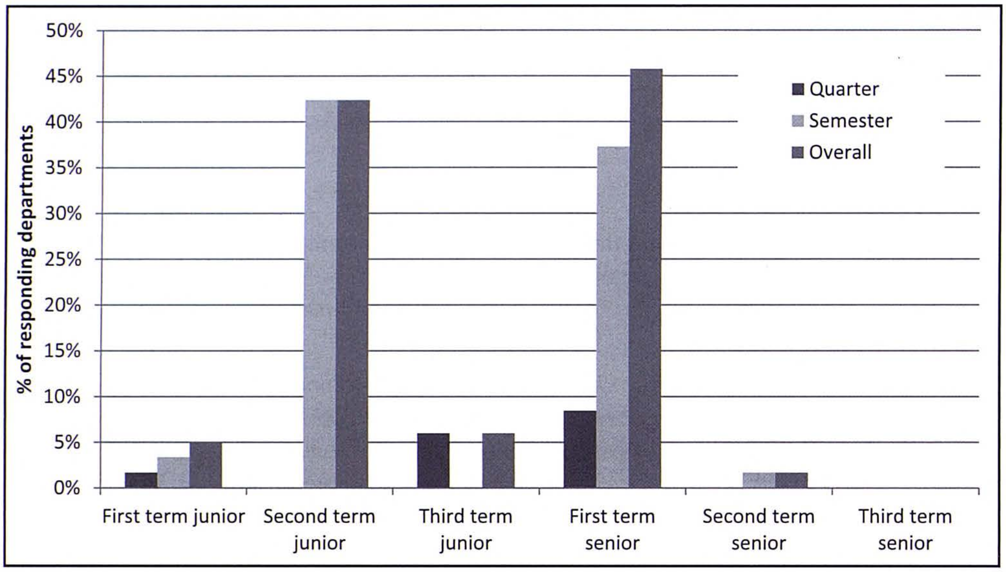

Figure 1. *2009-2010 offerings of CRE by term as reported by instructors.*

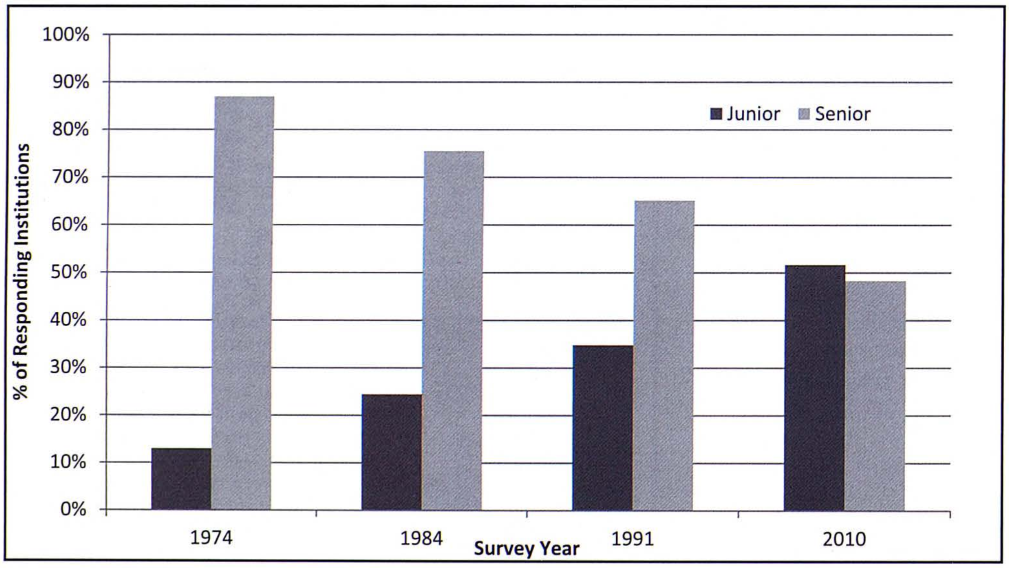

Figure 2. *Timing of first offering of CRE course. Data for 2009-2010 as reported by instructors.*

QUANTITY OF INSTRUCTION

Of the 60 institutions reporting, 55 indicated they offered a single course in CRE. The remaining five offered two courses. Of those institutions, three were on the quarter system. Those 60 institutions reported 3.7 h/wk total devoted to the course, broken up into an average 2.9 h/wk on lecture, 0.6 h on problem solving, and 0.2 h/wk on experimental laboratory. Only five of the 55 offer experimental laboratories, ranging from 30 minutes to 3 hours weekly.

In 1971, 3.06 h/wk of lecture and problem laboratory were reported, with 0.40 h/wk in experimental laboratories. The "typical" undergraduate experience has never included a laboratory specifically for this course. In 1971, 30% of universities responding indicated experimental labs, with an average reported time of 1.5 h/wk. The 1984 report indicated 6% of courses included a 1-hour experimental lab and 4% had a 3-hour experimental laboratory. The 1991 survey indicated an average of 3.41 h/wk in lecture, with an average of 1.91 h/wk experimental laboratory among the 22% of departments offering a laboratory as part of the CRE course. Figure 3 shows the historical changes in laboratory exercises associated with CRE courses.

CLASS SIZE

The typical size of a class section does not appear to have changed significantly over the past several decades, as shown in Figure 4. Since the bin sizes varied for each survey analysis, it is not possible to compare between survey results directly. In 2009-10, the average class size was 40. This falls in between the 1984 average of 43 and the 1990-91 estimated average of about 33.

When comparing section enrollment data with Figure 3, it appears that as class sizes increase, the number of programs incorporating laboratory exercises into a traditionally lecture course seems to decrease.

Classes are primarily taught by professional instructors, with only eight programs (12.5%) reporting teaching assistants (TA's) delivering lectures. Among those programs, a maximum of 10% of lectures were given by TA's, with the average being 3.7%.

The prerequisite courses declared by instructors in 2010 are given in Figure 5. Note that

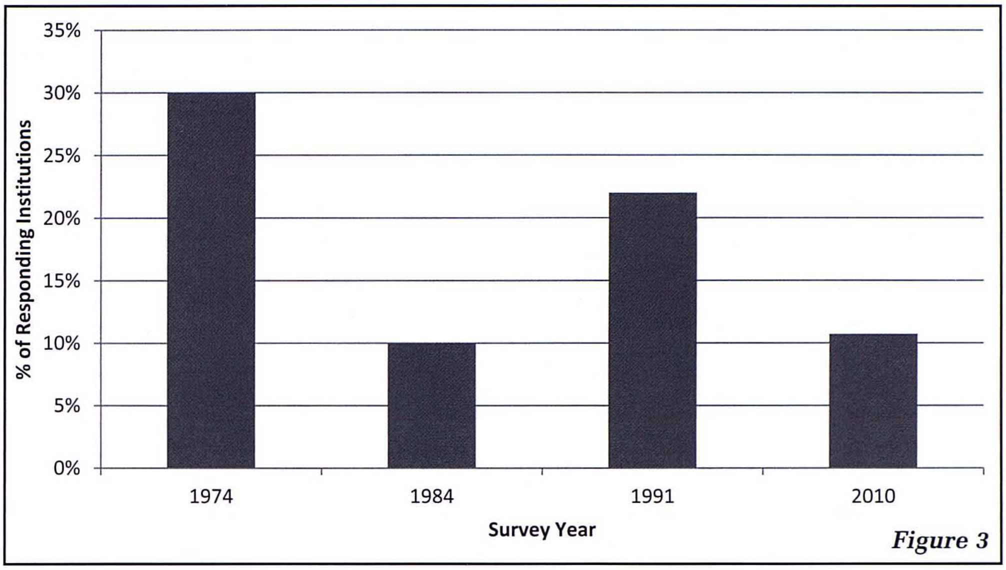

Figure 3

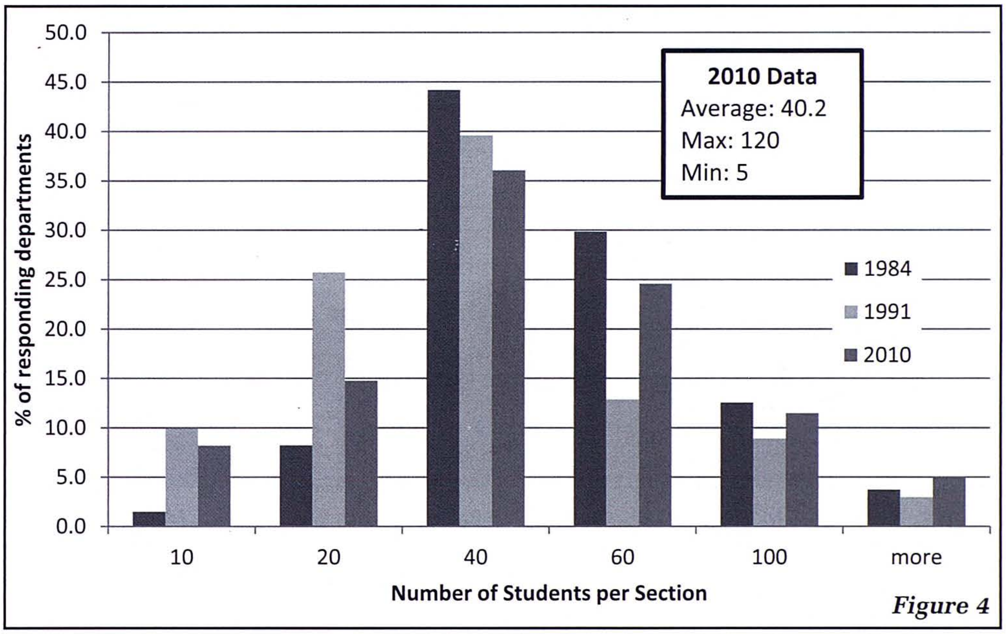

Figure 4

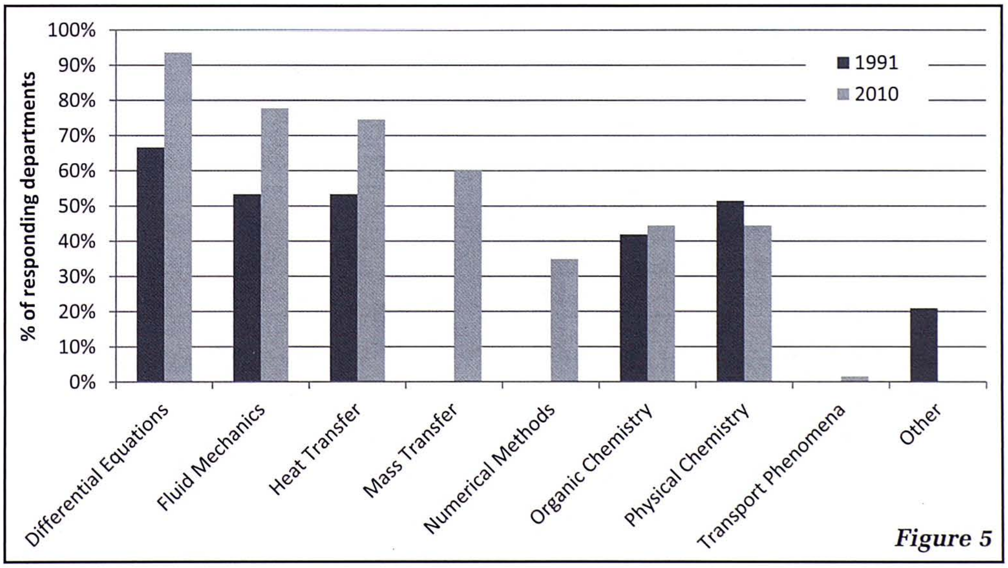

Figure 5

Figure 3 (top). *Percentage of responding programs offering laboratory exercises in conjunction with the CRE course. Data for 2009-2010 as reported by instructors.*

Figure 4 (middle). *Section size for the CRE course. Data for 2009-2010 as reported by instructors.*

Figure 5 (bottom). *Prerequisite courses (formal and informal) reported by instructors.*

transport-related courses have increased in frequency of requirement. Some programs simplify the prerequisite list by requiring "junior-" or "senior-standing," and do not give this full list of requirements explicitly in their course catalogs.

A wide range of student deliverables was required, as shown in Figure 6. When likely "open-ended" problems (independent and team projects, open-ended problems) are combined, about 54% of courses require open-ended design work. In the 1991 survey, 93% of departments indicated they would occasionally or often use open-ended design problems if they were available in their textbook. In that 1991 survey, 33% of departments indicated a project assignment.

The primary unit system used in CRE problems has also changed over time. Figure 7 shows how there appears to be a transition from a push to SI in 1984 followed by a return to American Engineering (AE) units in 1991 to a more balanced but leaning SI approach today.

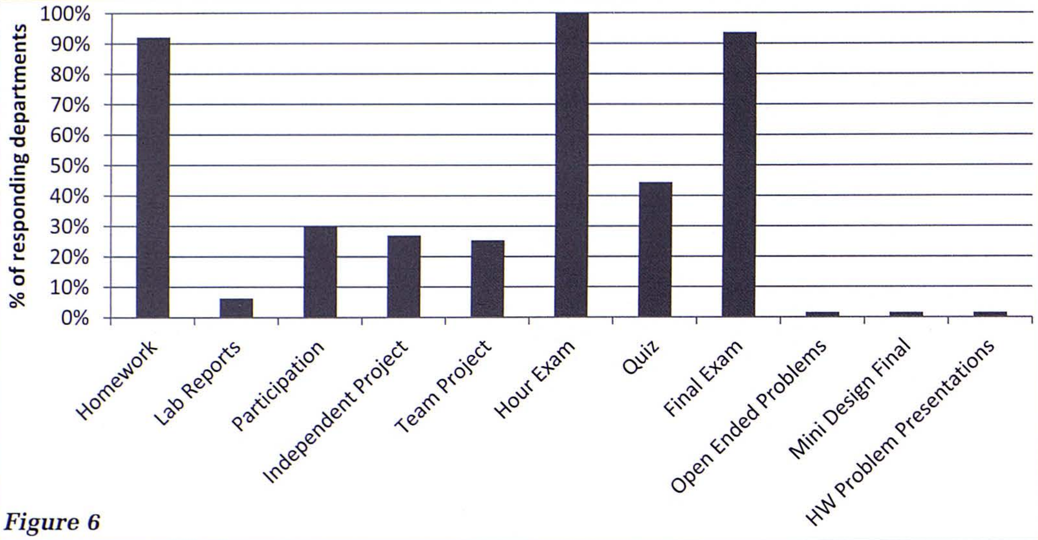

Figure 6

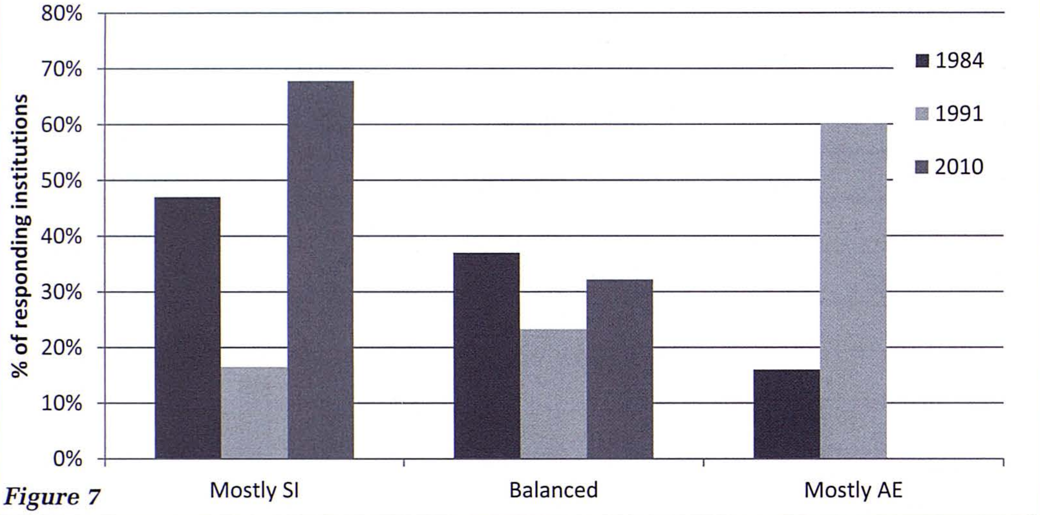

Figure 7

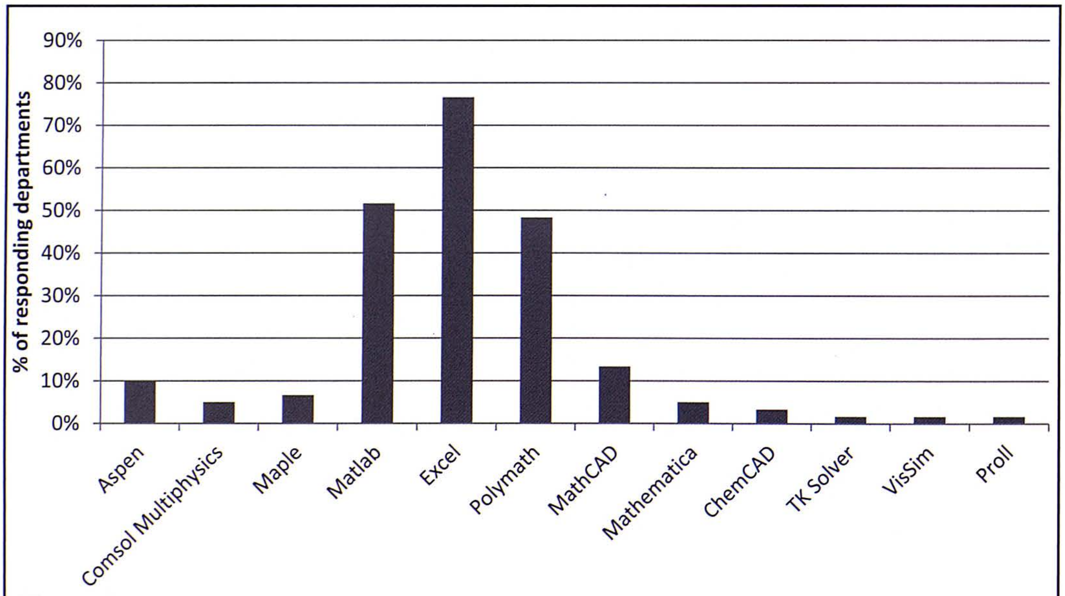

Figure 8

Figure 6 (top). *Deliverables required for the course in 2009-2010 as reported by instructors.*

Figure 7 (middle). *Characterization of unit systems used in problems encountered in the CRE course. Data for 2009-2010 as reported by instructors.*

Figure 8 (bottom). *Software used in the CRE course in 2009-2010 as reported by instructors.*

Software usage by programs was varied, as shown in Figure 8. Perhaps most notable is the lack of industrial process simulation combined with the emergence of finite element modeling. In 1991, the most common language/program reported was FORTRAN (71 programs) followed by Lotus (presumably the 1-2-3 spreadsheet), Basic, Pascal, and Flowtran.

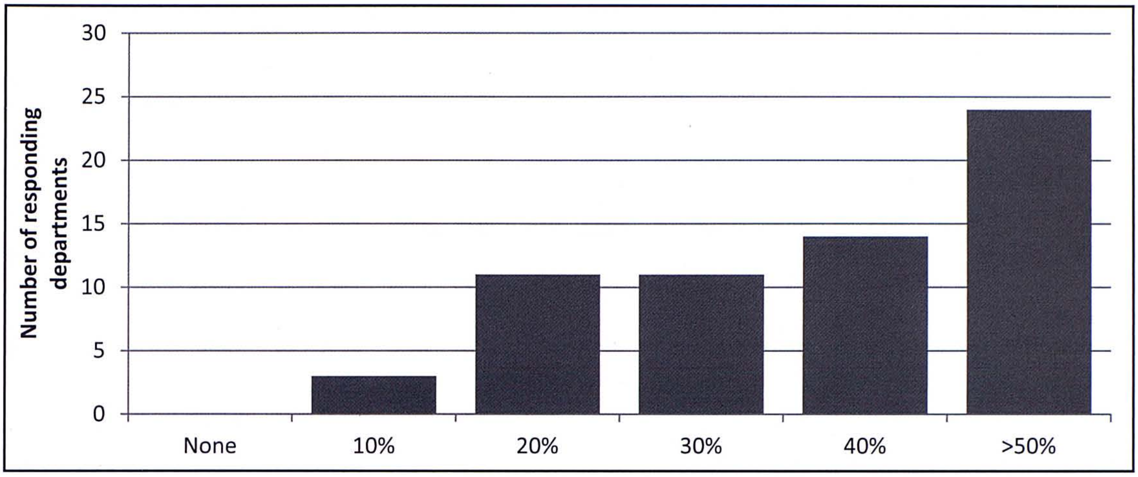

***Figure 9.** Percent of homework assignments requiring use of computer software in 2009-2010 as reported by instructors.*

The use of computer software in routine homework assignments is significant as shown in Figure 9. Other use of computers in the course includes use of course management software (CMS such as Blackboard) or web pages primarily for making available class notes and homework solutions. Some utilize Internet-based references for thermodynamic and transport properties, or to collect real-world operational data. Other schools provide exams from previous years for students to study, providing a "level playing field" for those without access to collections of old exams. Video from television programs like *MythBusters* is used for safety discussions. Animations collected from FEM/CFD software are used. Online reactor labs such as <*www.SimzLab.com*> enhance the course. Online texts are also used by some, such as Carl Lund's KaRE TExT, <*http://www.eng.buffalo.edu/Research/karetext/front_matter/title/info.shtml*>. The Chemical Safety Board also has relevant videos available online. Some textbooks offer significant supplementary material, including tutorial software, on their associated websites.

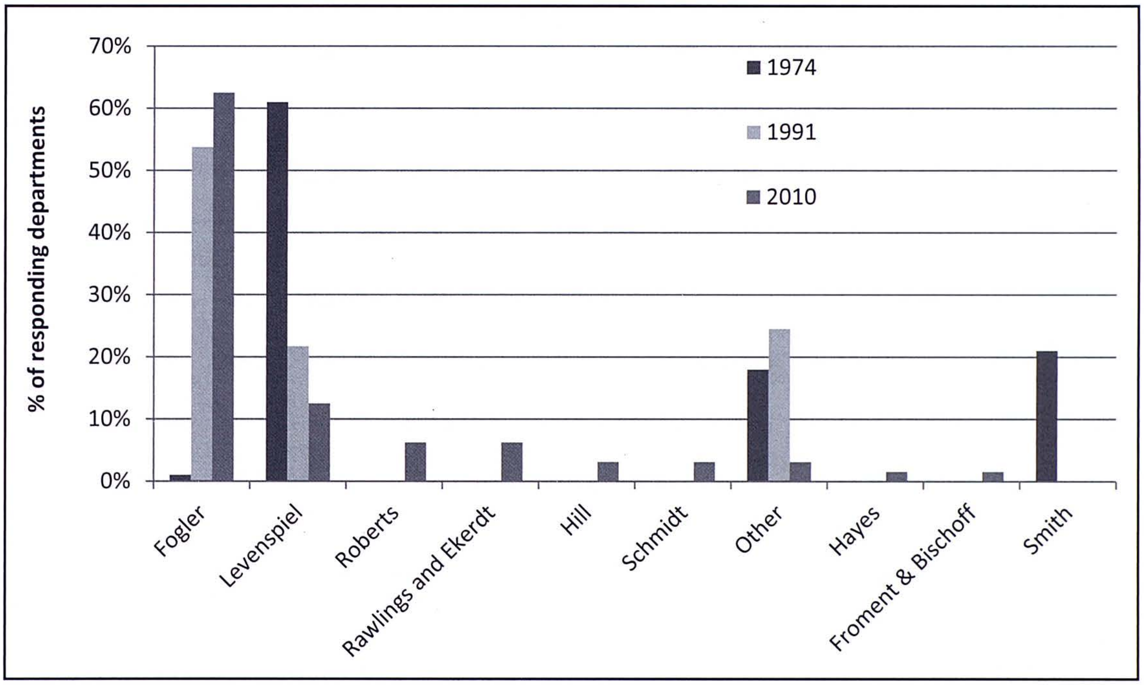

***Figure 10.** Adoption of textbooks. For a particular lead author, multiple editions may be represented. Data for 2009-2010 as reported by instructors.*

Textbooks reported as currently in use include:

- *Fogler,* Elements of Chemical Reaction Engineering, *4th Ed.*
- *Levenspiel,* Chemical Reaction Engineering, *3rd Ed.*
- *Roberts,* Chemical Reactions and Chemical Reactors
- *Rawlings & Ekerdt,* Chemical Reactor Analysis and Design Fundamentals
- *Hill,* An Introduction to Chemical Engineering Kinetics and Reactor Design
- *Schmidt,* The Engineering of Chemical Reactions
- *Froment and Bischoff,* Chemical Reactor Analysis and Design

Figure 10 illustrates the rise and fall in popularity of CRE textbooks over the past 36 years.

The changes in course topics are reflected in changes in textbook coverage and the use of those chapters. Figure 11 shows the usage of particular chapters in Fogler's textbook in both 1991 and 2010 among those institutions reporting adoption of the text.

There is general satisfaction with existing texts on the subject, though some would like to see a more concise textbook containing one semester's coverage. Some express an interest in additional coverage of safety topics and bioreactors, although as shown in Figure 11 the reported usage of a chapter on bioreactors has actually decreased since 1991. Some cite weak areas in specific textbooks in coverage of mixing, reaction kinetics, and non-isothermal reactor design.

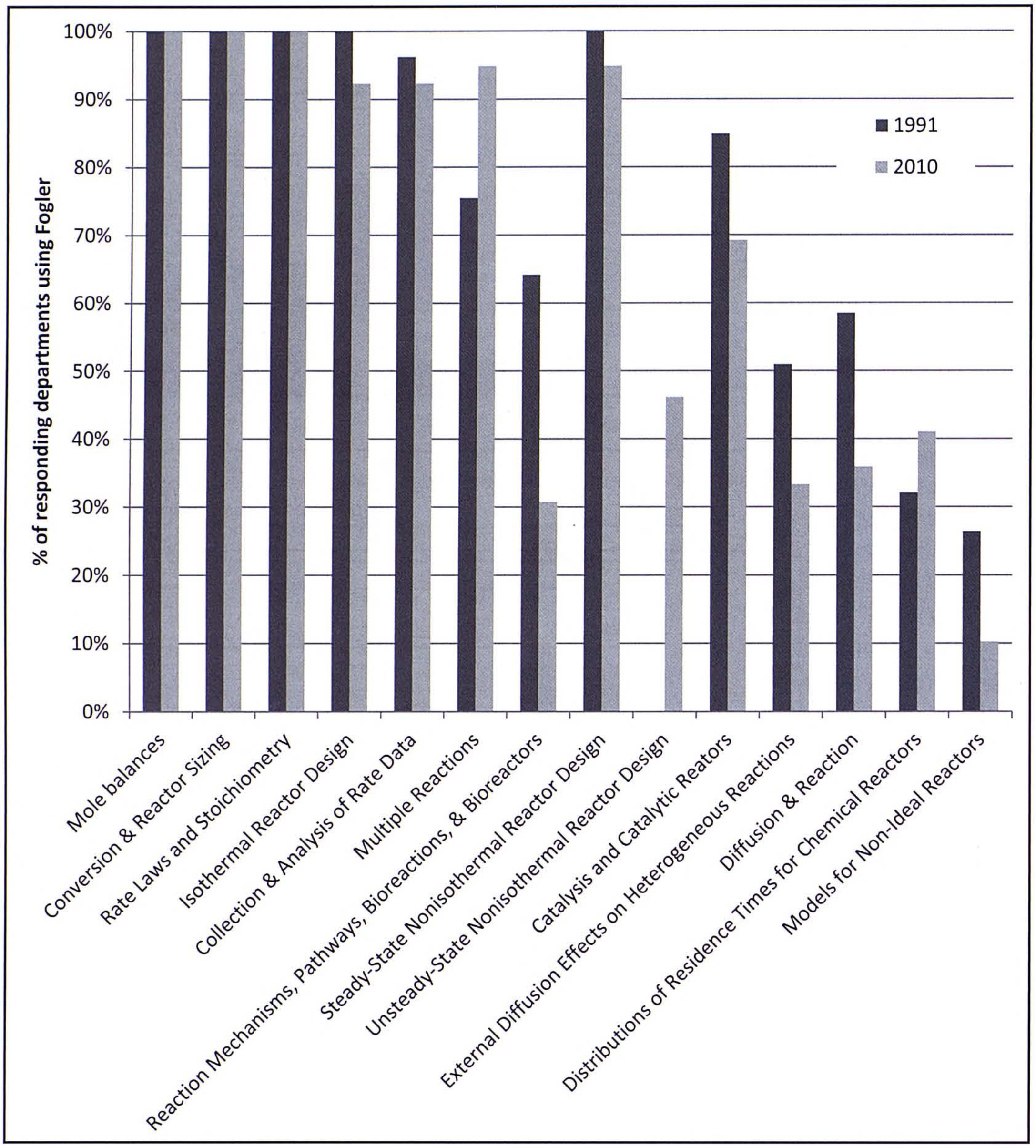

Figure 11. *Chapter topics taught as organized by Fogler's text. When editions have different titles, similar chapters have been combined. Data for 2009-2010 as reported by instructors.*

Along with changes in the core coverage, there have been changes in when core topics have been taught. The 1971 survey reported that 13% of programs covered the subject of reaction equilibrium in the CRE course. In 1984, this increased to 65% of responding departments indicating reaction equilibrium was taught in the CRE course, with 12% indicating it was taught in the thermodynamics course or sequence. Twenty-two percent responded "other" or "both." In 2010, only 5% of programs indicated the subject was covered in CRE.

Another topic considered in previous surveys is the theory of absolute reaction rates (a statistical mechanics approach). In 1974, about 58% of programs covered the theory of absolute reaction rates. The 2010 survey indicated 78% of programs covered the topic. Coverage of other emerging topics in CRE in the 2010 survey is presented as Figure 12.

Chemical engineering programs are likely to use this course for ABET outcomes assessment. The fraction of reporting programs using this course for ABET a-k outcomes is shown in Figure 13.

COMMON CONCERNS

Survey respondents were asked what they believed were the biggest issues encountered by students taking this course. The majority of responses indicated the following common challenges:

- *ODE solving skills*
- *Mathematical software skills*
- *Chemistry preparation*
- *Unsteady-state conservation law writing*
- *Dependence on "design equations" rather than fundamental conservation laws*

Concern over transfer of prerequisite knowledge to core courses is common, and is reflected in the list, as is the ongoing tension between engineering approximation and solution based on first principles.

THE ROLE OF INSTRUCTOR

Instructors often take different approaches to teaching. For many responding to the survey, instructors viewed themselves as a guide or facilitator, bringing students through the textbook material in a "rational way" and providing alternate explanations to the text. Others attempt to give a "big picture" view, tying various elements of the course (and the curriculum) together into a cohesive whole. For some, the role shifts as needed, from mentor to partner to coach depending on the student and the situation. Some instructors express the need for them to make the topic interesting and accessible, and to develop new examples and homework problems. The role as an evaluator was also commonly noted. Some indicate their role is to build on the textbook and not repeat what is explained well. Introduction of modern tools for design and simulation was emphasized by others. Another role cited by several instructors is a need to translate the ideality of a textbook to the challenges of the real world, including imperfect data, equipment failures, variability in feed stocks, management issues, etc.

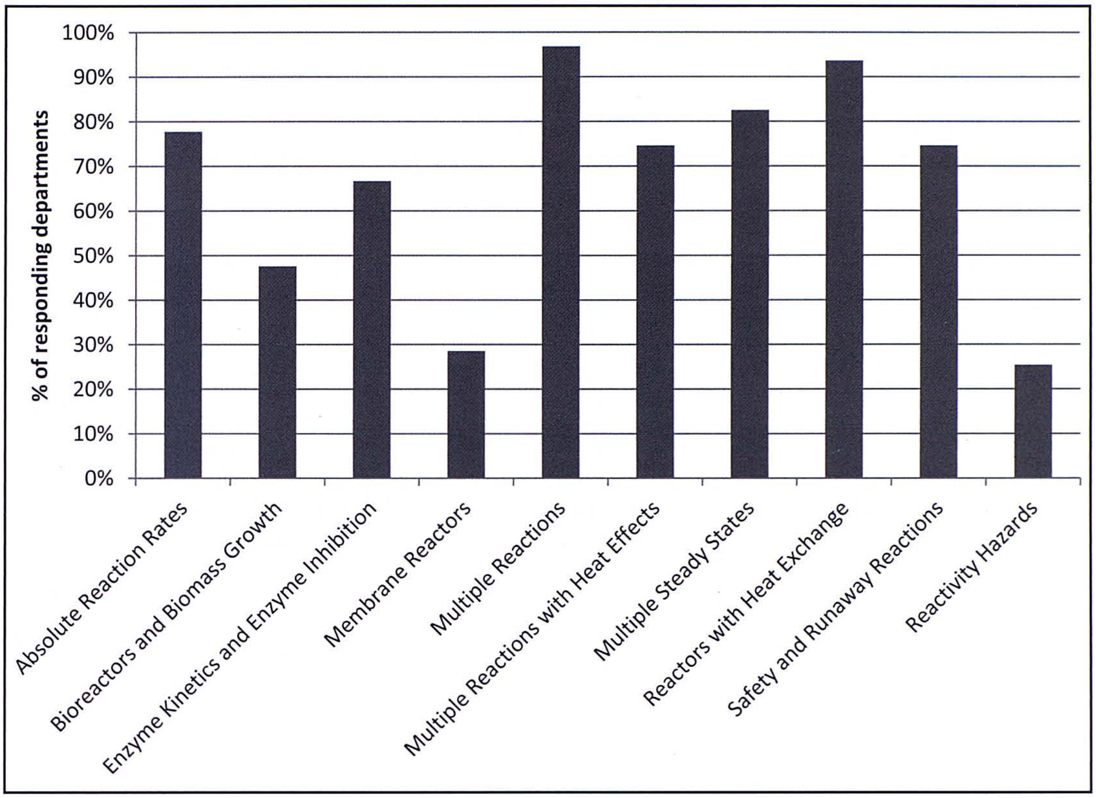

Figure 12. *Coverage of modern topics in CRE courses for 2009-2010 as reported by instructors.*

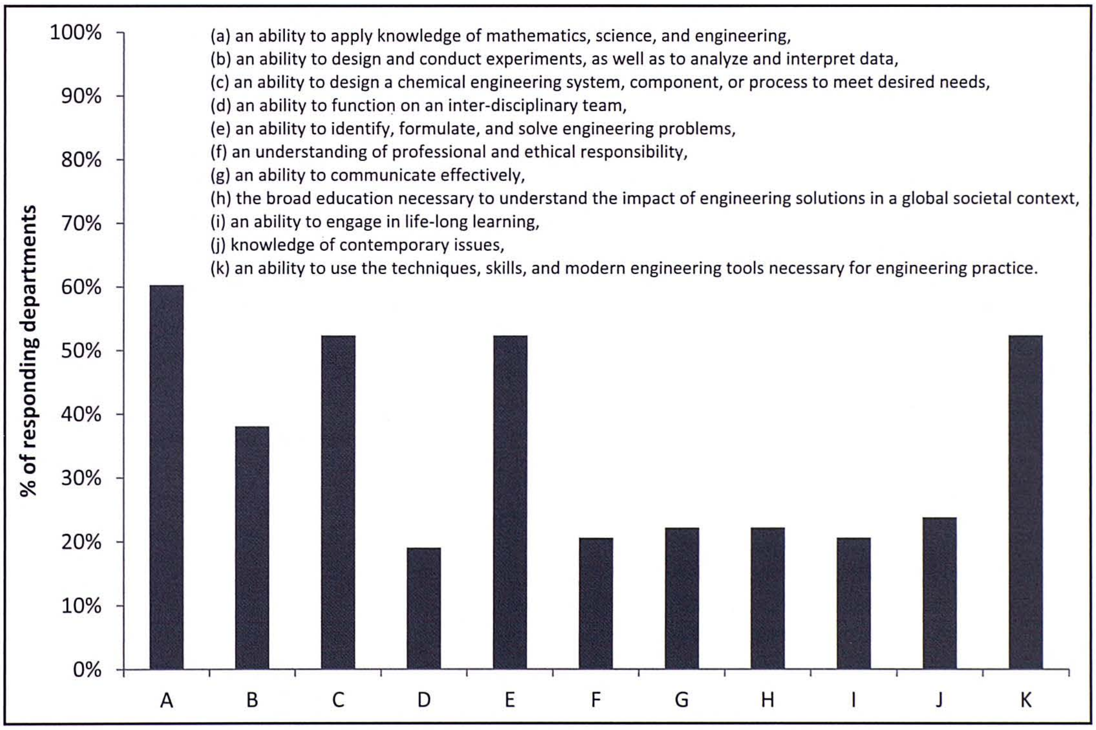

Figure 13. *Percent of programs using the CRE course as part of their ABET EC2000 assessment process for program outcomes. Data for 2009-2010 as reported by instructors.*

EFFECTIVE TEACHING METHODS

As part of the survey, responding instructors were asked to share some of the teaching methods and resources they believe were most effective. To follow up on those responses, a panel-led discussion was held at the 2010 AIChE Annual Meeting in Salt Lake City to build the description of methods and responses to the aforementioned concerns with teaching the course. Synthesized from both the survey and the discussion, the following topical elements were highlighted:

- ***Emphasis on fundamentals.*** *Starting from a mass balance rather than working from "design equations" was recommended. Algorithmic approaches are effective. Peer-to-peer instruction in problem sessions is effective.*
- ***Safety.*** *While safety has always been an important element of the course, it is likely to become even more critical in response to changes to ABET Chemical Engineering program criteria. Chemical reactivity hazard analysis will likely become a major topic in the course (or in a dedicated safety course) while runaway reactions will continue to be emphasized. There are opportunities to develop resources to aid teaching these topics. Safety should also be brought into class discussion frequently in the context of "what if" questions.*
- ***Software.*** *Fogler pioneered the development of CRE-related tutorial software in the 1990s and recently updated those resources. Finite element simulations and other CFD software can lead to effective introductions to more realistic reactor modeling. Spreadsheet-based rate simulators are available, as are simulations for complex reaction pathways with effective kinetics. The emergence of computational software has made complex systems like multiple reactions accessible,*[1] *but training on how to use the software effectively remains an issue. Programming, including working from a partially completed program or one with significant errors, can be effective in teaching concepts like examining the role of activation energy in multiple reaction systems or hot spots in a PFR. Others focus on setting up problems for computer solution in class, then executing the solution software. Having TA's run help sessions for software can be effective.*
- ***Laboratories.*** *Numerous laboratory systems were named, including: yeast fermentation; horseradish peroxidase marking; crystal violet dye decomposition; temperature-controlled flash photalysis (isomerization); RTD using dye injection; electrochemical water decomposition; alcohol decomposition/digestion; air bag detonation; ChemE Car design or demonstration; saponification of ethyl acetate in a batch reactor, a CSTR, and two CSTRs in series; methanol-to-gasoline conversion; photocatalytic destruction of aqueous pollutants; catalytic isomerization of butane in a PBR; reaction of diazydiphenylmethane with substituted carboxylic acids; reaction between sodiumthiosulfate and hydrogen peroxide in an adiabatic batch reactor; hydrolysis of crystal violet dye in an isothermal tubular reactor and a CSTR; isomerization of sulfite in a Parr reactor; alkaline fading of phenolphthalein in a batch reactor; hydrogen peroxide/sodium thiosulfate in an adiabatic batch reactor; catalytic methanol oxidation on a Pt wire; kinetic measurements of alkaline phosphatase (ALP)-catalyzed dephosphorylation of p-NPP in a CSTR; and reaction kinetics governing lactose conversion of dairy products. Note that the 1974 and 1984 survey reports include a list of all experimental systems reported by the respondents.*
- ***Mathematics.*** *Peer teaching was suggested as an effective way of developing student math skills. Game show approaches for in-class problem solving can be effective. A background in probability/statistics is becoming increasingly important in applying risk analysis to reactive systems, to catalytic reactions, and for sensitivity analysis. Propagation of error is another area where preparation could be improved. Some would argue that analytical mastery should be demonstrated before computational methods are used.*
- ***Economics and other practical considerations.*** *Some assert that discussing economics is impractical before formal coverage in a process design course, while others state it is important to bring practical limitations on reactor design and operation into the discussion during the course. Material handling issues (such as polymers) should be discussed. Some suggest having co-op students tell stories related to industrial practice. The role of rating existing equipment tends to be underemphasized compared to design. Team projects requiring reuse of equipment, equipment profiling, and detailed specifications are recommended. Others seek to replace generic reactions (*$A+B \longrightarrow C$*) with real chemical systems.*
- ***Emerging topics.*** *While exposure to bio- and nano- topics will continue to be important, energy will likely emerge as an area of emphasis in the short term. Ethics and safety will also likely increase in emphasis. Simulation-based engineering is developing as an important area of study and practice.*

The following list of effective teaching elements and suggestions represents a combination of the discussion and the survey.

- ***Critical thinking and conceptual learning.*** *The importance of always asking students "why," "how," etc., was emphasized. Many would argue the conceptual understanding of CRE is often more valuable than the computational aspects. Concept questions that can be used with (or without) classroom response devices (clickers) are available at* <http://www.learncheme.com> *courtesy of a project led by John Falconer. Additional conceptual-learning resources are available as part of the AIChE Education Division Concept Warehouse,* <http://cw.edudiv.org>.
- ***Group work.*** *Significant time is devoted to group problem solving by many instructors. Some formalize roles within the group: Thinker - is asked to solve problem, but does not get to use book or paper and pencil. Source of Knowledge - has access to book and problem statement;*

may only share verbally. And Recorder - the only one in the group with paper/pencil/calculator. They all must work together to solve the problem. Thinker will also be the group spokesperson to the rest of class.

- ***Asynchronous lecture.*** *One instructor uses pre-recorded lectures for instruction and spends class time on learning activities that build on the assigned preparation. A wide range of active learning exercises is then used, including teaching by analogies, inquiry activities, minute papers, contexts, debate, panel discussion, role playing, etc. Other instructors teach the course as a self-paced course with a computerized examination system. Another common approach is recording and archiving lectures live and posting for later review.*
- ***Novel homework approaches.*** *For one instructor, homework is an individual/team effort, where the team has the submission graded and individuals submit their own solution to verify effort. The grade is assigned based on a combination of the team and individual contribution. Another instructor requires written reflective assessment of homework submissions. Literature reviews and analysis are common.*
- ***Project- and/or Problem-Based learning*** *approaches are cited by several instructors.*

Analogies were often suggested as means of effective teaching. Particular examples include:

- *Site balances are compared to the number of chairs in a room.*
- *Batch reactors are compared to cooking vessels.*
- *Elementary reactions are compared to the likelihood of people (or pool balls) colliding. Two will hit fairly often, but three-way collisions are exceedingly unlikely.*
- *Tracer experiments are compared to observing a person in line at Space Mountain and then watching for when the same person emerges from the exit.*
- *The slab approximation for solving the n-order Theile modulus problem is as though a catalyst pellet has the peel of an orange in which all reactions happen; we then peel our pellet and "press" it flat into a flat slab.*

Some of the analogies take the form of in-class activities:

- *Rate limiting step: one student starts with a deck of cards and slowly deals them to a second student who passes them to a third who has to walk all the way across the room to pass each one to a fourth, etc., to "explain" a rate-limiting step.*
- *Residence time distributions: An activity where the students "own" a nightclub and want to know how long people stay at the club (too short and they don't spend, intermediate and they spend, too long and their spending dies off).*

The learning environment, both physical and contextual (what is done in class), can also play a role in helping students learn.

- *Active learning, as seen in many of the responses already detailed, is common and effective.*
- *Many instructors are deliberately reducing lecture and increasing discussion and group problem solving.*
- *Computer projectors are typically available, and many instructors project their solutions to problems and explore the models developed in class. PowerPoint is extensively used, as are online videos and images of real reactor systems. Some environments allow students to solve problems on computers alongside the instructor.*
- *Some classes are taught in a studio environment to facilitate interaction among students.*

In addition to program-determined outcomes, individual instructors tend to have areas of emphasis corresponding to their individual perceptions of importance of class topics. While no single course emphasizes all of these, individual goals for this course include:

- *Application of conservation laws*
- *Bioreactors*
- *Capstone integration*
- *Cost concerns*
- *Distinguish between ideal and nonideal reactors*
- *Distinguish between reaction-dependent factors and reactor-dependent factors*
- *Distinguish between stoichiometry and rate law*
- *Estimation methods*
- *Experimental analysis of rate laws*
- *Fundamentals of catalysis and surface reactions*
- *Industrial chemistry*
- *Intuition on reactor operation*
- *Numerical methods*
- *Optimization*
- *Overcoming equilibrium limitations*
- *Problem-solving skills*
- *Reaction system design (reactor + heat exchange + recycle)*
- *Reactor sizing*
- *Simulation skills*
- *Use of fundamental thermodynamics*
- *Utility of microscopic and macroscopic descriptions*

CONCLUSIONS

In many ways, Chemical Reaction Engineering may be taken as a bellwether of chemical engineering education in practice. It is one of the few courses taken exclusively by chemical engineering students; teaching practices in this course are therefore a good indicator of what is "typical" for the chemical engineering undergraduate experience.

The CRE course appears to be in the midst of a shift. It is moving earlier in the curriculum, as more programs offer the course in the junior year. The coverage is evolving, driven by technology (computational capability, FEM/CFD), by ABET (safety), and by other emerging topics. Despite the changes, the core coverage of the course has remained fairly constant.

Class sizes appear cyclical over the past several decades and appear to currently be around a local maximum, mirroring the national trends in engineering and chemical engineering enrollments.

Commonly accepted and literature-proven methods of instruction are commonly applied within the course. Use of "clickers" is common both as formative assessment and as a teaching tool. Resources supporting an emphasis on conceptual learning, such as publication of conceptual questions online, are increasing. Problem-based learning approaches and laboratories are available, although not in the majority of programs. Many programs are utilizing improved simulations of laboratories to obtain learning outcomes similar to laboratory exercises. Active learning approaches are widespread and varied, and those who use them are satisfied that they are effective.

ACKNOWLEDGMENTS

The authors would like to thank all of the instructors who completed this survey; the department chairs who passed on the request; and the University of Kentucky College of Engineering computing services, which hosted the survey. We would also like to acknowledge the assistance of Professor Don Woods of McMaster University for his review of the survey draft and continuing advice.

The full response data set is available from author David Silverstein upon request. The previous survey reports for this course are available on the AIChE Education Division website, <*www.edudiv.org*>.

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STUDENT ATTITUDES IN THE TRANSITION TO AN ACTIVE-LEARNING TECHNOLOGY

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Education research has provided substantial evidence that active learning strategies have a positive impact on student learning.[1] Using pre/post-test data of more than 6,000 physics students, Hake[2] found that courses that used active-learning methods had learning gains that were twice as large as the gains for classes that used only traditional lectures. Similarly, over a span of 13 years, Poulis, et al.,[3] studied more than 5,000 students in chemical engineering, electrical engineering, industrial engineering, chemistry, and physics classes. They found the pass rate in the classes that used active, concept-based instruction was 25% greater than those classes that used traditional lecture.

Student resistance, however, can deter implementation of these alternative active-learning approaches.[4] Furthermore, the prevalence and impact of student resistance is often understated. Students react to the change from sitting passively in lecture to becoming actively engaged in their own learning. This change challenges their assumptions about what learning involves and the appropriate roles of the student and the instructor,[5] revealing their expectations of what it means to be in a "good class"[6] and what should be "normal operating procedure."[7] It is argued that students know what works to achieve high grades in the traditional lecture environment and resist changes to "the system." One study of seven anatomy and physiology instructors who changed their classes to incorporate active-learning pedagogies found that five encountered significant student resistance.[8] In the context of *Problem-Based Learning*, Woods[9] identifies stages of coping with such changes that are similar to coping with a catastrophic event, including: shock, denial, strong emotion, resistance, acceptance, struggle, better understanding, and, finally, integration. While this model suggests that student resistance can fade with time, there is the danger that initial student resistance will cause an enthusiastic instructor to abandon innovative pedagogies. One goal of this study is to examine how student perceptions change with time as an active-learning technology is integrated into the department learning environment.

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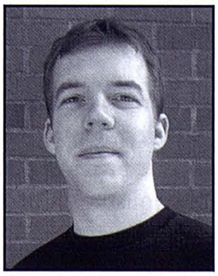


***Bill Brooks** is Ph.D. candidate in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. He is the primary programmer for the WISE learning tool. As an undergraduate student, he studied hardware engineering, software engineering, and chemical engineering. His thesis research involves investigating the interplay of content, pedagogy, and technology in student learning.*

Active-learning pedagogies have become enabled by technology-based classroom tools. For example, the use of Personal Response Systems, or clickers, has increased substantially.[10,11] Clicker technologies enable students to provide instantaneous feedback to instructor questions via a handheld device. Each clicker unit has a unique signal so that the answer from each individual student can be identified and recorded. Most clickers are limited to multiple-choice questions, however.

This study uses an alternative, technology-based tool, the Web-based Interactive Science and Engineering (WISE) Learning Tool.[12] Its use of computer technology permits a significantly wider range of learning activities than clickers allow. Specific to this study is the ability to ask students to provide short-answer, written explanations following multiple-choice questions. Pedagogically, the short answers provide students opportunities for metacognition through reflection.[13] Chi, et al.,[14] argue that the active process of explaining encourages students to integrate new knowledge with existing knowledge and leads to richer conceptual understanding. In addition, analysis of free-response explanations can provide researchers greater insight into the nature and range of student misconceptions.[15-17] A second goal of this study is to ascertain if students believe that providing written explanations increases the effectiveness of conceptual questions.

RESEARCH QUESTIONS

This study analyzes student responses over time to a survey about their perceptions of the use and effectiveness of WISE. Specifically, the research questions are:

1. *How do student perceptions change with time as a new active-learning technology becomes integrated into the department curriculum and culture?*
2. *Do students perceive that written explanations facilitate deeper reflection about their answers to the multiple-choice concept questions?*
3. *Is there any evidence in their statements of how students conceive conceptual learning?*

METHODS

This study spans five years and encompasses a cumulative total of 237 student participants. All students were enrolled in the second term of a junior-level, undergraduate Chemical Thermodynamics course at Oregon State University. The research was approved by the Institutional Review Board and participants signed informed-consent forms. The course is required for chemical engineers and taken as an elective by a small number of biological and environmental engineers. Therefore, each cohort has had similar programmatic experiences across the two and a half previous years of the curriculum. It is not possible to characterize the equivalence of each cohort in detail, however, and results of this study should be interpreted with that in mind.

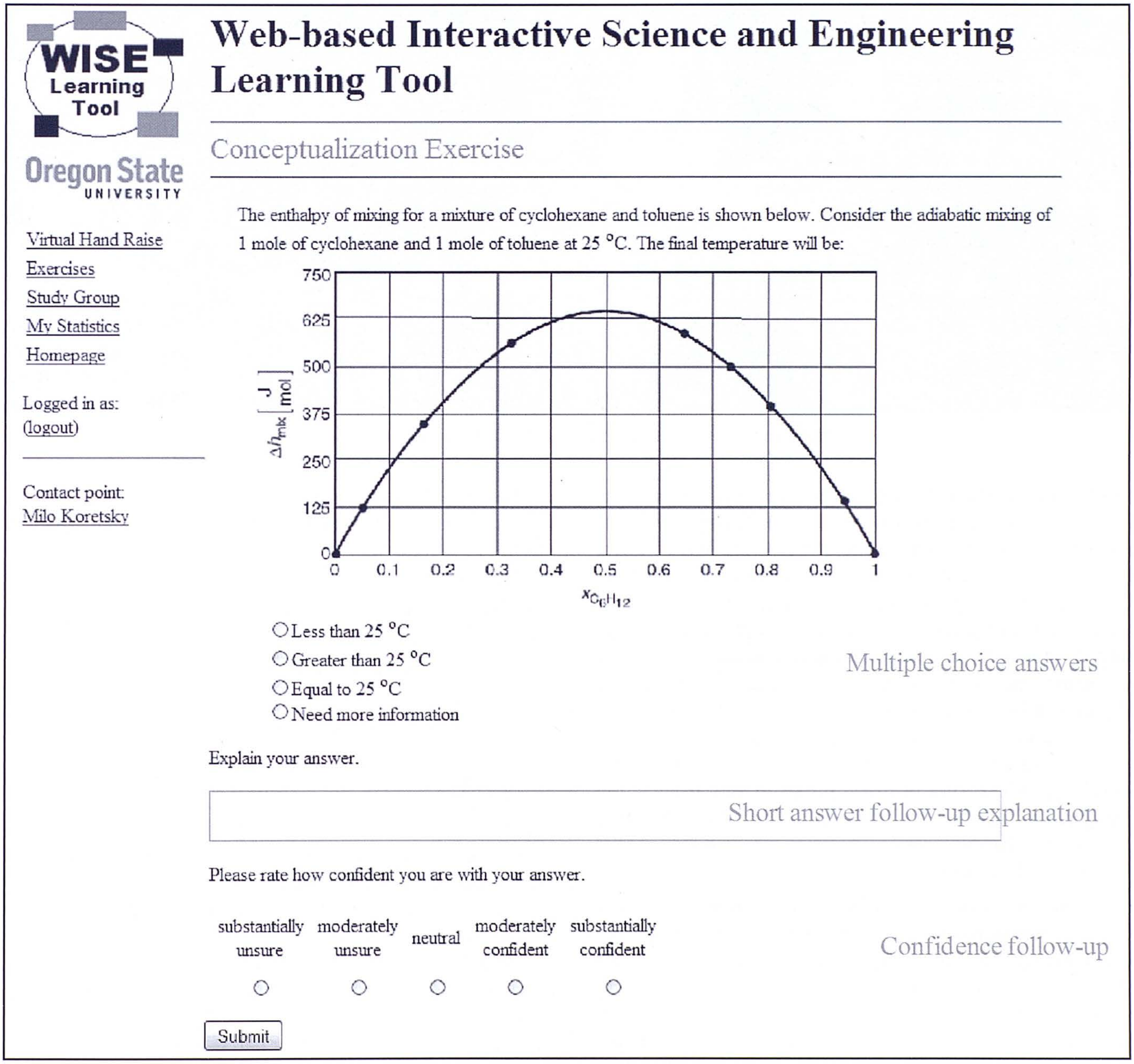
The Web-based Interactive Science and Engineering (WISE) Learning Tool is used to collect student responses.[12] WISE is enabled through a Wireless Laptop Initiative, which mandates that every student own a laptop computer. In the course studied in this paper, WISE was used once a week in the two-hour recitations that the entire cohort attended. Over the five years of the study, an increasing fraction of the cohort used Internet-capable, smart cell phones instead of laptops. The same instructor taught the course all five years. This instructor has substantial teaching experience, including with active-learning techniques. While this study represented the first experiences in using WISE, the instructor has implemented several other technology-based innovations in the curriculum.

WISE is designed for use in the context of a learner-centered class based on active learning and real-time formative assessment. It allows an instructor to pose questions that probe for conceptual understanding and supports a variety of student response types, including: multiple-choice answers, multiple-choice with short-answer follow-up, short answers, numerical answers, ranking exercises, and Likert-scale surveys. After the students have submitted a response to an activity, the instructor can review a summary of the results with the class. Depending on the class response, the instructor can choose an appropriate method (*e.g.*, peer instruction, instructor explanation) to reinforce or correct understanding. WISE also presents the opportunity to contribute meaningfully to the knowledge base in student learning in engineering. The use of the computer to probe student thought processes has been demonstrated as an effective education research tool.[18] Two elements of WISE make it particularly useful. First, students are assured of anonymity in their responses. Second, the automatic recording of student responses allows instant summarization of students' understanding and convenient collection of the results for analysis.

Figure 1 shows an example of a typical concept question as it would be displayed simultaneously on the students' laptops or smart phones. Such concept questions are designed to be conceptually challenging but typically require no computation so that students cannot rely solely on equations to obtain the answer. They focus on the most important concepts in a subject. The concept questions that were used were designed towards several possible objectives, including: to elicit or reveal pre-existing thinking in students, to have students apply ideas in new contexts, to ask students to qualitatively predict what will happen, to use examples from everyday life, or to have students relate graphical and mathematical representations. The question shown in Figure 1 asks the students to select a multiple-choice response, to provide a written explanation of their response (termed a "short answer follow-up"), and to rate their confidence. While this general format was the most common used in the course in this study, other question types were also used, including short answer, numerical answer, and ranking exercises.

Figure 2 (next page) shows a photograph of the use of WISE during a class. The logistics of delivery are based on the Peer Instruction pedagogy developed by Eric Mazur.[19] Students are first asked to respond individually to the concept question posed. They then self-select into small groups to discuss the answer. Next, the question is posed again and they respond individually. Finally, the instructor displays the results and can either explain the rationale for the correct answer or can lead a class-wide discussion, if appropriate. An analysis of student responses in WISE based on different delivery methods is reported elsewhere.[20] This type of active-learning pedagogy is often technologically supported with clickers. Clickers, however, are limited to the multiple-choice portion of the question. One goal of this study is to determine if students perceive that the reflective elements of questions like those shown in Figure 1 prompt deeper thinking and evidence-based reasoning.

Student perceptions of WISE were measured in each of the first five years that this technology-based, active-learning tool was used in the thermodynamics course. Year 1 represents the first time WISE was used throughout any course. Over the time of the study, WISE was integrated into other courses



Web-based Interactive Science and Engineering Learning Tool

Conceptualization Exercise

The enthalpy of mixing for a mixture of cyclohexane and toluene is shown below. Consider the adiabatic mixing of 1 mole of cyclohexane and 1 mole of toluene at 25 °C. The final temperature will be:

○ Less than 25 °C
○ Greater than 25 °C
○ Equal to 25 °C
○ Need more information

Multiple choice answers

Explain your answer.

Short answer follow-up explanation

Please rate how confident you are with your answer.

substantially unsure	moderately unsure	neutral	moderately confident	substantially confident
○	○	○	○	○

Confidence follow-up

Figure 1. *A sample interactive concept question, as the students see it in the WISE learning system. The "short answer follow-up explanation" prompts students to be reflective in their response to the multiple-choice question.*

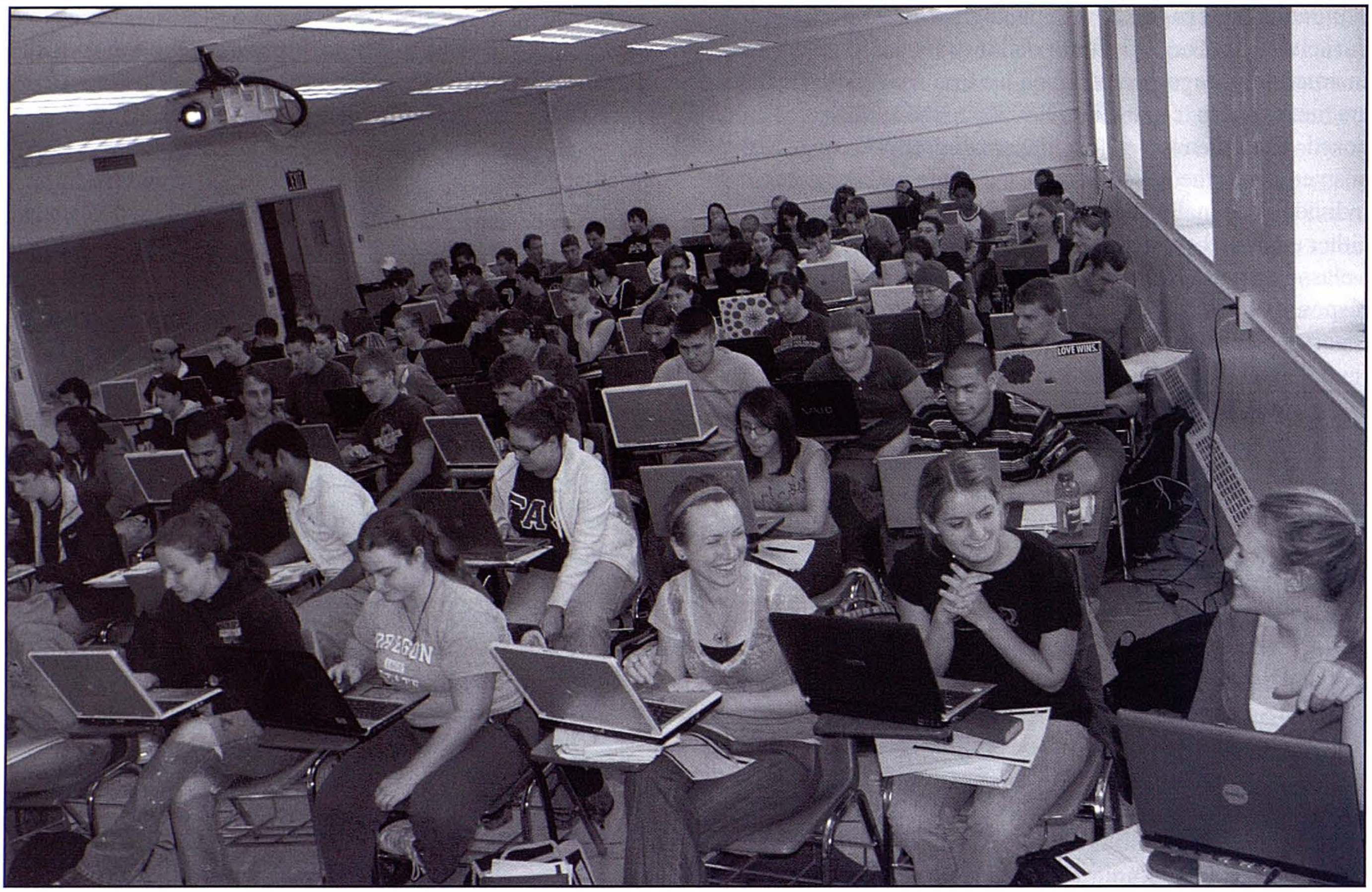


Figure 2. *Students engaged in a learning activity using WISE.*

in the curriculum, including the three required sophomore-level courses that preceded thermodynamics. The department culture also facilitated the transition to using WISE. There is broad collegial and administrative support for this active-learning initiative, some of which is described as follows: faculty in the program were willing to adopt the technology into their courses; the department has historical value of curricular innovation and a focus on student learning; the department head understands the value of and is supportive of curriculum reform; the faculty demonstrate respect for previous curricular innovations by the faculty member who developed WISE (the primary author of this paper); and many of the faculty who integrated WISE also voluntarily participate in an engineering education research seminar led by this faculty member.

The survey instrument consists of eight Likert-scale statements (1=strongly disagree to 5=strongly agree) and three questions that require written comments. The Likert-scale statements are shown in the first column of Table 1. Statements 1 through 6 were adapted from a similar study on clickers.[21] Statement 8 was written specifically to address Research Question 2 in this study. A non-parametric Kruskal-Wallis test[22] was used to compare student responses to each statement by year and to determine if the median rank was statistically different (*i.e.*, not statistically the same). This test does not assume the populations are normally distributed, but does assume that the distribution for each year has the same shape.

Three free-response questions were also asked, as follows:

1. *Describe any problems specifically based with technology that you encountered when WISE was used in class,*
2. *Describe any benefits of using WISE in class, and*
3. *Write any additional comments or thoughts.*

In this study data are reported for Years 1, 2, 4, and 5. In each of these years the course was taught in the same classroom, which had adequate wireless coverage for all of the students' laptops. The class was moved to an alternative room in Year 3 that had insufficient wireless coverage to allow all of the students in the class to simultaneously access WISE on their laptops. This classroom environment presented an additional challenge in delivering the technology-based, active-learning pedagogy. Eventually, the class was divided in half, with one half using WISE and the other half doing a pencil and paper activity, and then the activities were reversed. This delivery was significantly different from the four other years. Consequently, this cohort was excluded from the study.

RESULTS AND DISCUSSION

The average ratings for the eight Likert-scale statements and the number of responses for Years 1, 2, 4, and 5 are shown in Table 1. A five-point scale was used with a rating of 1 indicating the student "strongly disagrees" with the statement, a rating of 3 being neutral, and a rating of 5 indicating the student "strongly agrees." All of the responses in Table 1 indicate that, on average, students viewed all eight statements favorably each year. In Years 4 and 5, six of the eight statements had average ratings greater than 4. The highest-rated responses are in bold. In three of the years, students agreed most strongly with the statement that their written reflections, the "short-answer follow ups," were useful in promoting reflection and encouraging deep thinking. They also indicated they were more engaged intellectually and more actively involved through WISE. The lowest-rated statement was the one that asked if WISE, specifically, was responsible for improved awareness of misunderstandings.

Figure 3a plots the percentage of students who agree with each statement (ratings of 4 or 5) for each year in the study and Figure 3b plots the percentage who disagree (ratings of 1 or 2). For all statements, the proportion of students who agree with the statement is much greater than the proportion of students who disagree. Additionally, for most statements it appears that the percentage of students who agree trends upward with time and the percentage of students who disagree

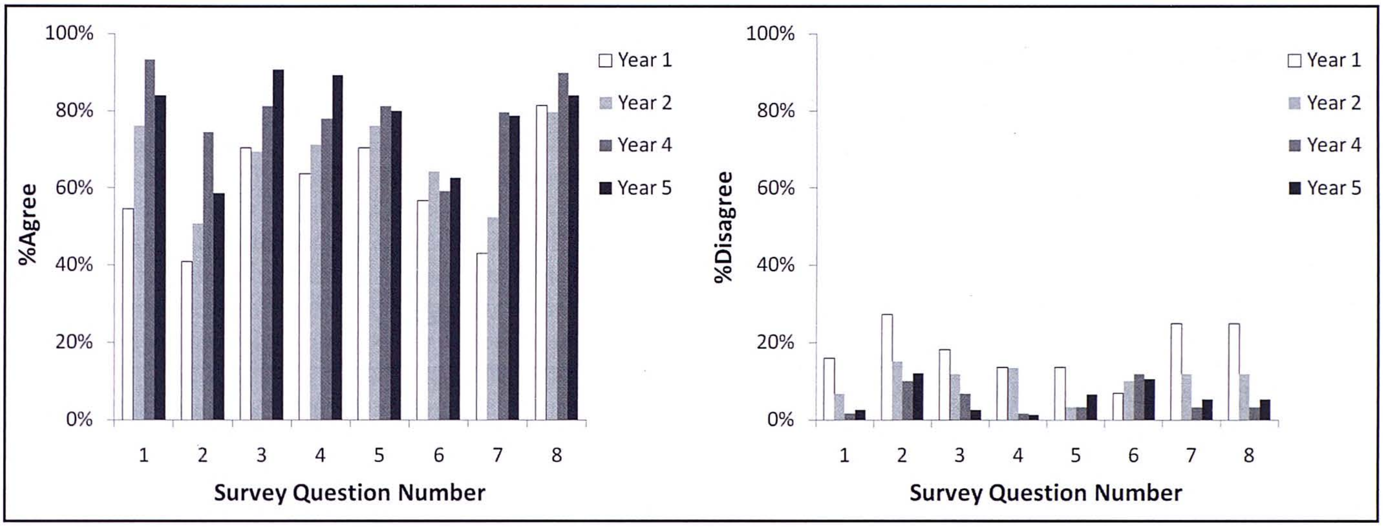


Figure 3. *a) Percentage of students who agree (rating of 4 or 5) with each of eight statements in the student survey for the four years of the study. b) Percentage who disagree (rating of 1 or 2). See Table 1 for the statements.*

TABLE 1

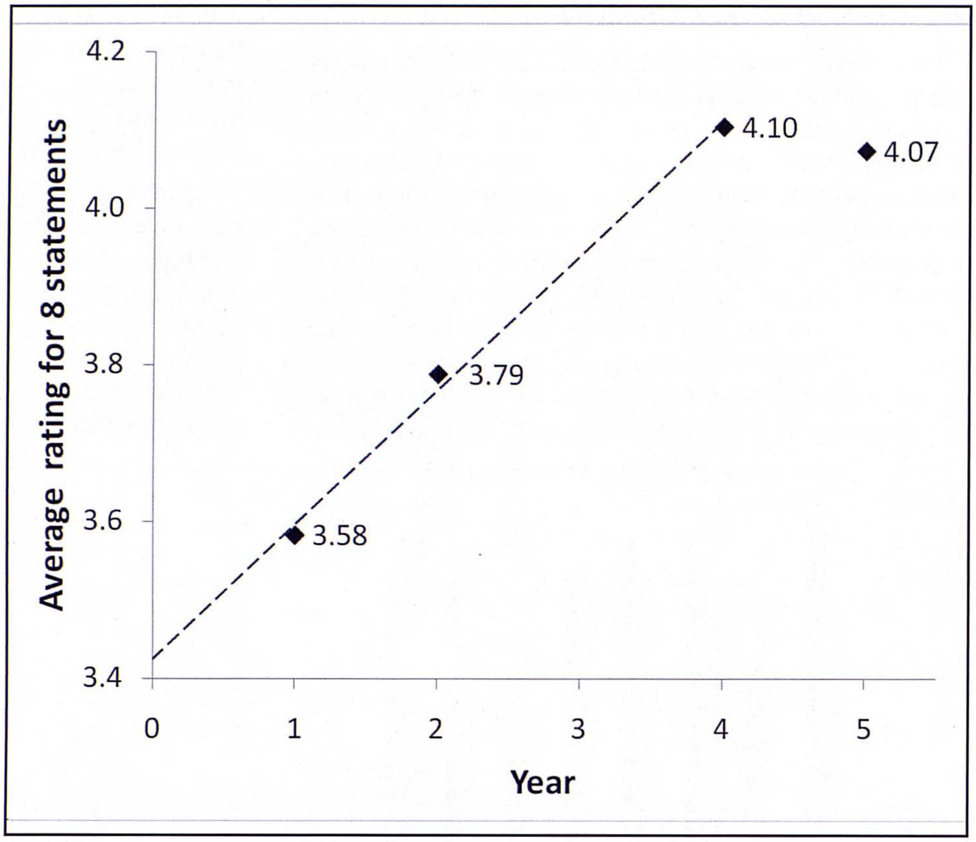
Average scores of student survey at the end of the Chemical Engineering Thermodynamics 2 class, using a Likert-scale (1=strongly disagree to 5=strongly agree).*

In the last column, the p-value for the Kruskal-Wallis test, applied to the "unsteady-state" data in Years 1, 2, and 4.

Statement	Year 1 (N = 44)	Year 2 (N = 59)	Year 4 (N =59)	Year 5 (N =75)	p
1. In this course, I am more aware of my misunderstandings than in courses taught by traditional methods.	3.52	3.95	4.37	4.16	0.0000
2. The change in awareness of my misunderstandings is due to WISE.	3.05	3.37	3.76	3.64	0.0004
3. Using WISE helps me to understand the concepts behind the problems.	3.61	3.69	4.22	4.24	0.0001
4. I am more actively involved in class when WISE is used	3.84	3.88	4.15	**4.36**	0.3371
5. I have to think more in class sessions that use WISE than those that do not.	3.89	4.00	4.19	4.15	0.3899
6. Seeing the class responses to a concept question (bar graph) helps increase my confidence.	3.57	3.78	3.64	3.75	0.4059
7. If WISE was used in other classes, my conceptual understanding in those classes would be better.	3.16	3.49	4.08	4.09	0.0000
8. The short answer follow-ups to multiple-choice questions helped me to think more about the question and the answer.	**4.02**	**4.14**	**4.41**	4.20	0.0307

* The highest-rated responses are in bold.

Figure 4 (right). Aggregate average student rating of all eight statements plotted vs. the year of the study. Year 1 was the first time WISE was used for a course. The line represents a fit to the proposed "unsteady-state" process of student normalization.



trends downward. This change of perception with time is discussed in the next section.

Change in Attitudes With Time

Figure 4 plots the aggregate average rating of all eight statements vs. year of the study. Year 1 represented the first comprehensive use of WISE in a class. The ratings show a proportionate increase in Years 1-4, and then level off in Year 5. We attribute Years 1 through 4 as a transition (unsteady-state) period as this technology-enabled, active-learning tool is integrated into the curriculum at OSU. We believe that Year 5 indicates student attitude at "steady-state" or "saturation" for this course. For convenience, we label it as "steady-state" for the purposes of this paper, but acknowledge this assignment is speculative. The initial 4-year period corresponds to one generation of college students.

Based on this observation, we asked, "For which statements can we state to greater than 95% confidence that the ratings had changed over Years 1 to 4 of the study?" The p-values for such a statistical analysis using the Kruskal-Wallis test are shown in Table 1. Five statements (1, 2, 3, 7, and 8) have p-values less than 0.05. We can infer that there is statistical evidence that student ratings for these statements improved with time. Three statements (4 - 6) have p-values much greater than 0.05. This result indicates that there is not statistical evidence that students are rating these higher with time. Said differently, even though ratings appear to generally trend upward for statements 4 - 6, we cannot state with confidence that this trend is not due to statistical variation from year to year.

The statements that show statistically significant upward trends are distinctly different in character than those that do not. The ones that do not show significant changes represent more direct in-class activity ("more actively involved in class" or "think more in class sessions") and emotional responses ("bar graph helps increase my confidence"). On the other hand, those that show a significant upward trend are more interpretive, specifically about learning ("aware of my misunderstanding," "understand the concepts," or "my conceptual understanding would be better"). These latter types of statements are more likely to be influenced by students' subjective attitudes about the technology-enhanced learning tool. In a similar study on student perception, White, et al.,[23] also found initial reticence of students to admit the extent to which they have learned in the transition to a problem-based learning pedagogy.

The nature of answers to the free-response questions of the survey is consistent with this analysis. In Year 1, there were several statements indicating trepidation about the use of WISE. Several students expressed concern that the class time used for the active-learning exercises would detract from the amount of material covered (*e.g.*, "I felt like if we did not use WISE we would be able to cover much more material in the class."). Additionally, the following response alludes to some general negative discourse among the cohort: "I think you will have recieved (sic) enough info from students on why they didn't like it, I think that the questions asked with reguards (sic) to concepts help us to direct our thinking, but the concepts cannot be written in some book, read and learned without a thought process happening." These types of statements were absent from student comments in the Years 2, 4, and 5, suggesting a shift in the normative expectation from other students.

As WISE has been delivered over time, students' perceptions of its effectiveness improve, and they view it as more beneficial to their learning. There are several factors that could contribute to this change in student attitude, including:

1. *Assimilation of WISE in the department's learning environment*
2. *Improvement of the technology*
3. *Improvement in the instruction*

We believe that the most significant factor in the change in attitude for the cohorts in this study is the assimilation of WISE in the department's learning environment, *i.e.*, with time WISE has simply become part of the normative student expectation about learning. The first year it was used in the junior-level thermodynamics course, there was interaction with seniors (some of whom were retaking the class) who did not use this technology the year before. We speculate that this disparity sets up a dynamic of "why do we have to do it when they didn't?" More importantly, over the next two years, WISE was integrated into the three sophomore-level courses (Material Balances, Energy Balances, and Process Data Analysis). Thus, by Year 4, most students had three previous courses where WISE was used to facilitate active learning. The effect of this assimilation is clear when reading the free-response survey items from Years 4 and 5 where students frequently contextualize their comments for the thermodynamics class based on experiences from past classes (*e.g.*, "No problems in this class but some classes I have had have had problems with logging on or submitting answers"). Such curricular integration makes students less likely to dismiss this pedagogy as a pet project of a maverick instructor. When adapting innovative educational technology and pedagogy, as much as possible, it is useful to have a coordinated approach through a set of courses in the curriculum.

The second factor affecting students' perception of WISE is the technology. Especially with new technologies, even small glitches in performance can be greatly amplified in student perception. Since the software was developed in-house, a "continuous improvement" approach was used where small changes in the software were made in response to student feedback. Perhaps more importantly, the wireless connectivity in the College of Engineering has systematically been improved over the five years of this study. In response to the survey question, "Describe any problems specifically based with technology that you encountered when WISE was used in class," the percentage of students that stated there were no technology-based problems increased in each year of the study (except Year 3 as explained above). In Year 1, 51% of the students reported no problems, 59% in Year 2, 67% in Year 4, and 78% in Year 5. The most common problems cited were network connectivity (27% in Year 1 to 14% in Year 5) and battery life (10% in Year 1 to 5% in Year 5). These problems are generally at the level of the technology infrastructure and not associated specifically with the WISE software application.

Finally, teaching with learner-centered pedagogies requires that the instructor deploys a different set of skills than the traditional didactic lecture. There can be a transition as an instructor adapts. For example, Keeney-Kennicutt, et al.,[24] describe student attitudes about a web-based writing and assessment tool they used in a general chemistry course. Their study shows a similar pattern in student response growing more favorable over time; however, unlike the study reported in this paper, their initial perceptions were overwhelmingly negative (four out of the five items had more students disagree than agree). They attribute the change in student attitudes over the seven semesters in the study primarily to the adjustments they made in instruc-

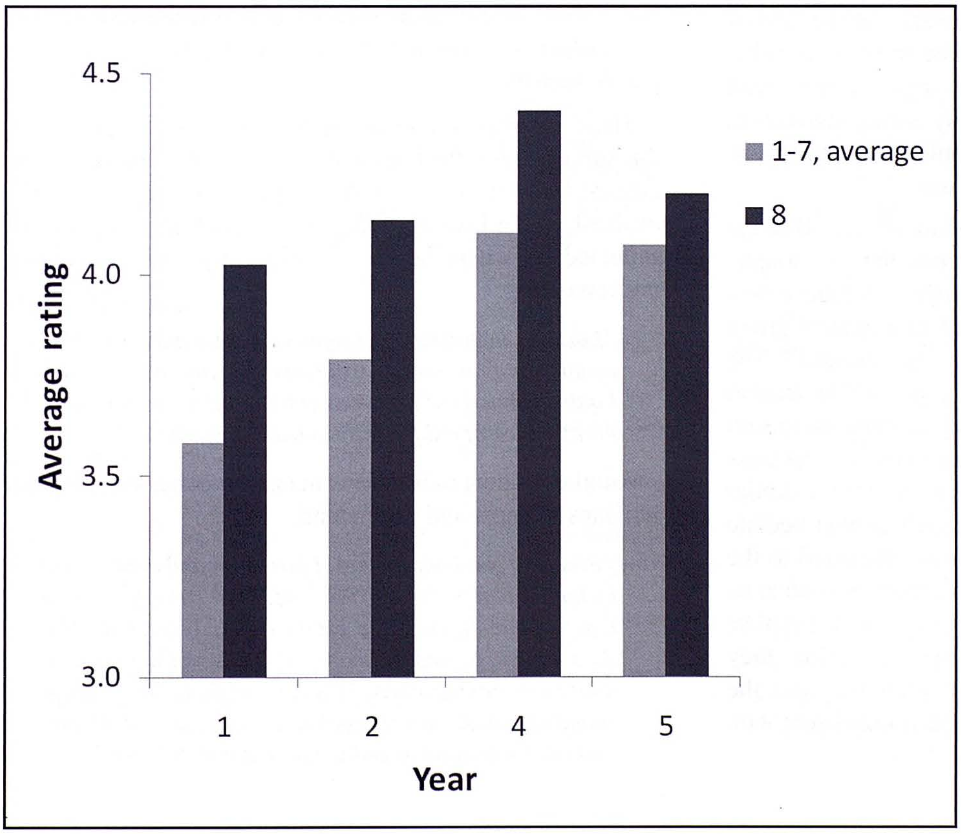


Figure 5 (left). *Student aggregate average rating for statements 1-7 and average rating for statement 8 vs. year in the study.*

tion and implementation. While aspects of instruction were changed over the five years of this study, we believe that this effect was the least significant of the three discussed above.

It is critical for instructors adapting innovative pedagogies for the first time (and for administrators evaluating those instructors) to recognize that there is a transition period as students adjust to the new expectations. In this context, it is important to be prepared for the possibility of strong initial student "push back." As shown in Figure 3b, the percentage of students in this study who disagree, part of whom initially formed a "vocal minority," decreases dramatically with time from as high as a quarter of the cohort for some statements in Year 1 to just a few percent in Year 5. This type of student resistance within a class can be attenuated by repeatedly explaining to students the purpose of and rationale for the active-learning technique[6] and building rapport in the classroom.[25] Due to the factors cited above, however, it may take several years for students to completely normalize expectations and reach "steady-state."

Perception of Value of Written Reflection in Learning

As Table 1 shows, in Years 1, 2, and 4, the average rating for statement 8, "the short-answer follow-ups to multiple-choice questions helped me to think more about the question and the answer," had the highest value of all the Likert-scale statements. It was also rated very favorably (4.20/5.00) in Year 5. Figure 5 compares the aggregate averages of the other seven statements to the statement 8 rating for each year of the study. Clearly students viewed the reflective written explanations as beneficial to learning. One of the advantages of the laptop-based technology interface of WISE is the ability to develop a more diverse range of question types than available with clicker technology. In their view, simply asking students to reflect on their answer choices to multiple-choice questions affords reflection and encourages thinking.

A recent study of the use of clickers in Introductory Biology studied the effect of displaying an "intermediate bar graph" after students answered a concept question, but before they discussed with their peers as compared to a control group where the intermediate class result was not shown.[26] The authors found this practice negatively impacted the answer choices following peer discussion. They attribute the result to students unthinkingly accepting the consensus of the class in selecting the second multiple-choice answer. In a similar study, we found that when using WISE, such an intermediate display had no effect on student choice as compared to the same type of control group.[20] While other factors need to be considered in comparing the two studies, one could speculate that by having students provide a written reflection, they were prompted to already be "thinking" when they saw the intermediate results. Such an explanation is consistent with the disparate results between studies.

With the increasing use of clickers in the classroom, we suggest that the development of a written free-response capability into Personal Response Systems would be fruitful for clicker manufacturers. Alternatively, instructors could have students write answers with pencil and paper while using these active conceptual questions. This modification may only partially realize the desired reflection, however. Finally, as an alternative to laptops, programs like WISE that integrate written reflection can be enabled by smart phones. Over the five-year study, unsolicited responses from students commenting on their use of smart phones have steadily increased (0 in Years 1 and 2, 2 in Year 3, 12 in Year 4). Of these 14 responses, only one cited a technical issue using the phone (lower than the rate for laptops). To the contrary, most respondents seemed to be boasting about using a smart phone (*e.g.*, "I had no problems. I enjoyed being able to use my iPhone instead of bringing a computer to class"). Reflection plays a critical role in promoting learning. We believe that there is a great opportunity in using smart phone technology to promote reflection in this active-learning pedagogy.

Student Interpretation of Conceptual Change

A primary goal of the active-learning pedagogy enabled by WISE is to transcend beyond asking students to memorize definitions and algorithms and instead to focus on conceptual learning. Posner, et al.,[27] believe that a critical condition for such conceptual change to occur in a student is when his/her prior knowledge comes into cognitive dissonance with new knowledge. The resolution of this conflict can lead to learning if the concept being examined is restructured and the conception is incorporated into an integrated schema, like that of experts.

There are many comments to the free-response portion of the survey that reflect students' own interpretation of conceptual learning based on their experience with the WISE-enabled, active-learning pedagogy. For example, one student reflected on where he/she has difficulty with conceptual understanding:

> *"I usually understand concepts that are intuitive, it's the counter intuitive areas I struggle most with. In this course I quickly found out what was counter intuitive and learned how to think of it differently to make it intuitive."*

Another student indicated a change in his/her view of what it means to know and understand:

> *"From my previous courses, I just learn and apply. I will be honest that, in most of the case, I just know how to do it mathmatically (sic) and get the right answer, but...what does it mean behind the math, I don't think I'm that aware until I got into this class. This class required lots of understanding instead of just problem solving. And I did learn alot (sic) and experienced a different way to learn."*

These comments reflect a very individual interpretation of their experience in alignment with the goals of the curricular innovation. It should also be realized, however, that throughout the term this goal of conceptual learning has been made explicit to students, so their comments should be considered with that in mind.

CONCLUSION

Student attitudes were measured over the first five years that the WISE-based active-learning pedagogy was introduced into a junior-level chemical engineering course. In general, students viewed this learning experience more favorably with time. This study has several ramifications for instructors considering technology-based integration of pedagogy into the classroom. Elements that affect student perceptions include: (1) degree of curricular integration and the department culture, (2) the ability to improve technology as problems arise, and (3) modifying instruction appropriately for this type of pedagogy. In addition, students view the activity of providing written reflections as very helpful to learning. Technology developers and course designers who desire pedagogical integration of conceptual questions might consider ways to prompt such reflection in students, although more study is needed to see if improved student performance does indeed align with the student perceptions seen here.

ACKNOWLEDGMENTS

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CENTRIFUGAL PUMP EXPERIMENT
for Chemical Engineering Undergraduates

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Undergraduate curricula for chemical engineers of most universities include experimental studies of absorption, distillation, fluid flow, heat transfer and other topics. All these experiments seek to give undergraduates a practical sense of the basic principles they need to understand during their careers. Recently, the undergraduate chemical engineering program at the University of Missouri began to change its use of the experiments. This change came about from concerns of students who often felt that these experiments (two classes, total of six credit hours), while useful, did not give them a practical understanding of the principles and practices they would deal with in industry. Also, the dean of the college was encouraging faculty to apply "experiential learning" techniques in their classes.

Experiential learning may be defined as "a process through which a learner constructs knowledge, skill, and value from direct experience." In this paper a brief outline of the major activities of experimentally learning are presented. These activities are initiated with a "problem" that challenges the student. The problem is followed by the student "developing a plan, testing this plan against reality to discover a solution, and reflecting on the results to determine whether there are other or better solutions to the problem. The testing phase requires the learner to apply information that is often left out of the learning that occurs in a traditional education setting. Application is a critical component that identifies this theory as experiential and provides educators with a framework for designing learning activities in which students combine thinking with doing."[1]

Centrifugal pump experiments have existed in various chemical engineering laboratory curricula throughout the years.[2, 3] These experiments primarily focus on the pump's properties, including head and shaft power. LabView has also been shown to assist in student's understanding of a phenomenon when data collection is in real time.[4]

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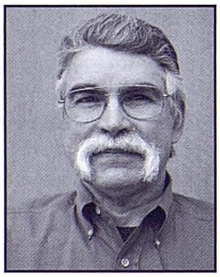

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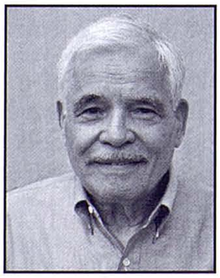

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To address this need for better learning of chemical engineering principles, several new modular experiments were added to our curriculum and some of the existing apparatus were modified. One of these new modular experiments involved the performance characteristics of a centrifugal pump. This experiment included observations of the pump performance characteristics and applications of the experimental results. One illustrated application was a typical industrial scenario: "What will be the centrifugal pump flow rate and cost of pumping power?"

This report describes the centrifugal pump experiment conducted during the spring 2010 semester; instruction used experiential learning techniques, and results indicate the experiment was a notable enhancement to the laboratory curriculum.

CENTRIFUGAL PUMP EXPERIMENT: DESIGN AND CONSTRUCTION

The centrifugal pump experiment's success was partially due to the incorporation of computer data collection and control technology.

The data collection sources were: pressure, flow, motor voltage and current, and impeller speed. The speed was determined by a pulse signal, six pulses per revolution. The current was measured with a magnetoresistive device. These source signals were direct inputs to a LabView program.

The centrifugal pump is powered by a brushless DC motor. For the control of this DC motor a simple-voltage-regulator device was utilized. This device allowed impeller speed control by the LabView program; precise to ± 1 rpm. The speed control system is possibly unique and cost-effective. The motor control operation was very reliable and user friendly based on extensive testing.

Appendix A provides a detailed description of the design, construction, and cost of the centrifugal pump system.

Using LabView data collection and control software, data were collected instantaneously from the system, which contained a water feed tank, centrifugal pump, flow meter, pressure gauge, and finally a flow-control valve, see Figure 1. The LabView software transmitted flow rate, head, impeller speed, temperature, voltage, and amperage of the system into a data file. In addition, power input to the pump was determined from the product of measured voltage and amperage. The centrifugal pump impeller speed was an independent variable and was controlled by setting the voltage in LabView. All experiments were carried out at room temperature. The centrifugal pump system used during the Spring 2010 semester is shown in Figure 2 (page 54).

OPERATING PROCEDURE

The centrifugal pump operating procedure is presented in Appendix B. The operation of the pump system generated a performance curve, head vs. flow, as a function of impeller speed (N). A brief summary of the procedure follows.

The students set the pump to a constant impeller speed value while the valve was completely open (The inlet, suction-side valve to the pump needs to be fully open before turning the pump on). Once the system reached steady-state, which takes only a minute as evident in LabView, data collection was started. The valve was slowly closed until completely closed. The completely closed valve corresponds to the pump "shut-off" head. The student was then able to change the impeller speed of the pump, and collect performance curves for as many speeds as needed. System operations or raw data were collected in Excel spreadsheets for the students to analyze, correlate, and present in their laboratory reports.

The students were also instructed to test the centrifugal pump Affinity Laws for systems with constant impeller diameter. These include:

$$Q \, \alpha \, N \tag{1}$$

$$H \, \alpha \, N^2 \tag{2}$$

$$P \, \alpha \, N^3 \tag{3}$$

where Q is flow rate, H is head, P is output power, and N is the pump's impeller rotational speed, revolutions per minute.[5] For example, the Affinity Laws were applied to calculate a standardized head for the system, as follows:

$$H_{std} = H_{max}\left(\frac{N}{N_{max}}\right)^2 \tag{4}$$

PRACTICAL APPLICATION

The students were also expected to calculate the cost to cool 1,000 computers using one pump per computer over the course of the year. To simulate the use of the centrifugal pump to provide cooling water to cool computers, it was assumed that the pumps would operate 8,000 hours of the year at constant speed.

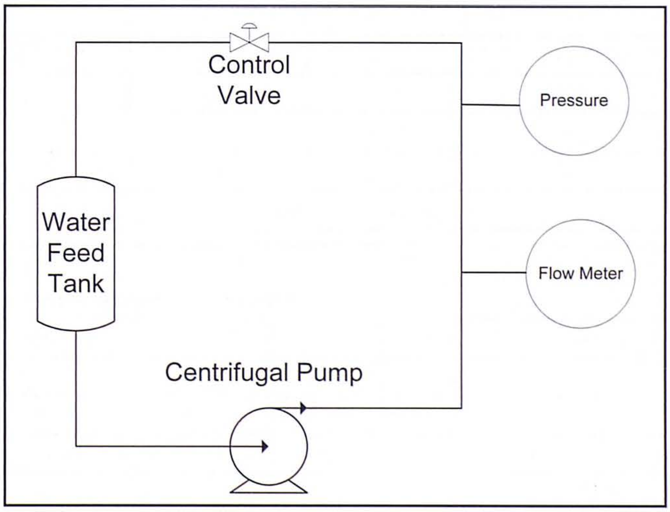

Figure 1. *Schematic of the centrifugal pump experiment.*

To do this, an arbitrary set of tabulated data for system frictional losses as a function of velocity was provided by the instructor, see Appendix C. This data set needed to be correlated by the student(s). The system curve provides quantitative values for the friction losses, as a function of flow rate through the virtual system of computers. Frictional loses were assumed to be proportional to the square of velocity.

The intersection of the curves, pump head vs. flow and system head vs. flow, determines analytically and graphically the estimated local best efficient point (BEP) for pump operation. The absolute best efficient point is where the flow and head are at the greatest efficiency.[6] The students found the local best effect point, which is the maximum efficiency for a given flow rate. This is commonly done in industry to size pumps and to specify system steady-state operating conditions. The BEP values for pressure and flow at a constant speed were then used to calculate the power input and output of the pump, and find the efficiency of the pump at its operating conditions. These values were determined by the following formulas; see Appendix D for sample calculations:

$$P_{\text{Input}}\,(\text{Watts}) = V\,(\text{Volts}) * I\,(\text{Amps}) \tag{5}$$

$$P_{\text{Output}}\,(\text{Watts}) = P_{\text{Output}}\,(\text{J/s}) = Q\,(\text{L/min}) * 1\ \text{min}/60\ \text{s} * 1\ \text{m}^3/1000\ \text{L} * P\,(\text{kPa}) \tag{6}$$

$$= Q\,(\text{m}^3/\text{s}) * (\text{N/m}^2) \tag{7}$$

$$\text{Efficiency}\,(\%) = \frac{P_{\text{Output}}}{P_{\text{Input}}} * 100 \tag{8}$$

From these calculated results, the students were also able to calculate the yearly cost of electricity, as follows:

$$\text{Cost(Annual)} = \text{Number of Pumps} * (\text{Operation Time} * P_{\text{Input}}) * \text{Cost of Electricity} \tag{9}$$

By doing this, students completed a preliminary design estimate for the cost of pumping power and system flow characteristics.

TABLE 1
The Best Efficient Point (BEP) and the Efficiency for Each Centrifugal Pump Impeller Speed Value

Impeller Speed (RPM)	Flow Rate (L/min)	Pressure (kPa)	Efficiency (%)
2010	1.35	6.55	22.3
2340	1.61	7.95	25.1
2610	1.81	9.90	28.7
3330	2.36	16.7	38.8
3510	2.52	19.3	42.2

TABLE 2
The Amount of Energy and Annual Cost of the Individual Pumps at the BEP

Impeller Speed (RPM)	Efficiency (%)	Energy Input (W)	Annual Cost per pump ($)*
2010	22.3	0.66	2.72
2340	25.4	0.85	3.50
2610	28.7	1.04	4.28
3330	38.8	1.69	6.96
3510	42.2	1.92	7.91

* Annual = 8000 hours at constant speed

EXPERIMENTAL RESULTS AND DISCUSSION

Results are calculated in Appendix D and presented below.

A) Performance and System Curve

Each student or team of students was able to provide a complete performance and system curve from the experiment, as shown in Figures 3 (page 54). In this figure, the ordinate is the pump's pressure head and the abscissa is the water flow rate, with each performance curve at a constant impeller speed. In the relation of head vs. flow rate for each impeller speed, the intersection of the performance curve and system curve gives the point where each pump will operate. The intersection of these lines is also where the frictional loss for each pump design is at a minimum, and makes the point the best efficient point (BEP).

B) Best Efficient Point

From Figure 3 and Excel spreadsheets, the students determined the BEP's for the system curve provided. For the BEP values, the students were also able to go back to the raw data and retrieve the voltage and amperage values to calculate input power to the pump, and pump efficiency, as listed in Table 1. A typical set of data for the pump performance has been provided electronically and is available at <http://www.ornesengineering.com/Marrero_Vanderslice_Data.xls>.

TABLE 3
Affinity Analysis Results for Operation of a Centrifugal Pump

N (rpm)	Q (L/min)	Q_{std}	Error %	ΔP (kPa)	ΔP_{std} (kPa)	Error %	P_{output} (W)	P_{std} (W)	Error %
2130	1.44	1.52	5.65	6.22	6.99	12.32	0.149	0.18	18.68
2633	1.82	1.88	3.34	10.04	10.68	6.33	0.305	0.33	9.88
3302	2.34	2.36	0.79	16.44	16.79	2.13	0.641	0.66	2.94
3741	2.67	2.67	0.08	21.45	21.55	0.47	0.955	0.96	0.55
4382	3.13	3.13	0	29.57	29.57	0	1.543	1.54	0

C) Application

The complete cooling problem is presented in Appendix C, and the energy requirements from Table 1 were used by the students to solve this problem. Students assumed the BEP values represent pump operating conditions (pressure and flow rate) at highest system efficiency. From this they assumed the pump system for computer cooling would operate at these conditions. The students then calculated the annual operating cost for each pump (see Table 2). Results indicated that at the lowest impeller speed, the cost was at a minimum. It may be noted that the efficiency for the pump increased with impeller speed (see Table 2, second column).

For the annual cost of 1,000 pumps at the lowest operating cost, the lowest cost is \$272/yr.

D) Affinity Analysis

The students were also able to standardize the data to find the error of the system as shown in Table 3. This practice, while simple, was shown to be largely absent from the knowledge of students before the laboratory, but once the concept was explained, the simplicity and practicality of it surprised many students.

CONCLUSION

The experimental apparatus and protocol demonstrated the performance characteristics of a centrifugal pump, verification of affinity laws, and application of pump flow rate/head data with system hydraulic characteristics to specify steady-state operating conditions, BEP. In addition, at BEP values, the annual cost of pumping for a practical application was estimated. The new centrifugal pump experimental study was "hands-on" about the practical use of pumps, and students responded to this lab experience as a more practical learning opportunity than the previous lab.

RECOMMENDATIONS

The relatively low cost and time needed to design and construct the centrifugal pump lab, plus the considerable learning by the students, implies that the lab experiment was successful and could be used at other universities, if needed.

EDUCATIONAL ASSESSMENT

Students were asked to include a brief paragraph that described their educational assessment of the centrifugal pump lab. Nineteen assessments were received. A major consensus was an appreciation of the lab's practical value. Some students mentioned the value of hands-on learning of the various principles; most students thought that the application to industrial practices was far more interesting.

In addition, many of the students thought that as essential as pumps are for the chemical process industry, they had been minimally, if at all, taught in previous classes. The students also appreciated the hands-on experience with a working pump system with real-time results (observations, calculations, and graphs). Also, students thought the knowledge of how to find the Best Efficient Point was worth learning.

Finally, in several assessments, students asked for added complexity to the lab system. Namely, to include more changes in variables, such as pump size, impeller speed at a constant control-valve setting, and determination of energy efficiency for these changes in pump design and operation.

From the Spring 2011 semester, seven assessments were collected and the predominant themes of the educational assessments are included in Table 4.

TABLE 4
Education Assessments by Students of Experiential Learning Experience- Centrifugal Pump Lab
(Spring 2010)

Favorable	Constructive
Practical value (4)	Experiment too simple (2)
Hands-on learning (3)	Add more features, such as pumps of different size, control valves, etc. (2)
Interesting industrial application (1)	
Learned new information about centrifugal Pumps (4)	Determine effects on energy consumption of any additional features (1)
Real-time experimental results (2)	
BEP determination valuable (3)	

(n) = approximate number of students who made similar comment.

ACKNOWLEDGMENTS

The authors appreciate the assistance provided by Philip D. McCormick and for supplying data and sample calculations. Also, many thanks to Mike Carraher for preparing the pump system circuit diagram.

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APPENDIX A. DESIGN, CONSTRUCTION, AND COST OF CENTRIFUGAL PUMP SYSTEM

Description

The pump motor is a brushless dc motor that operates between approx. 5V and 12V. The pump will shut off at voltage greater than 12V. The pump requires housing: XSPC Premium Laing DDC Clear Acrylic Top -Version 3.0. The motor's starting voltage is higher than the minimum operational voltage, and the speed of the pump varies with voltage range. Also the pump will not run in reverse.

Analog output voltage from LabView ranges from 0 to 10V. The circuit contains both Scaling trim pots and offset trim pots Offset trim pots have +/-15 V connected on either side. Scaling trim pots are in the feedback loops or on the input.

The circuit was designed to be both inexpensive and run on a single power supply.

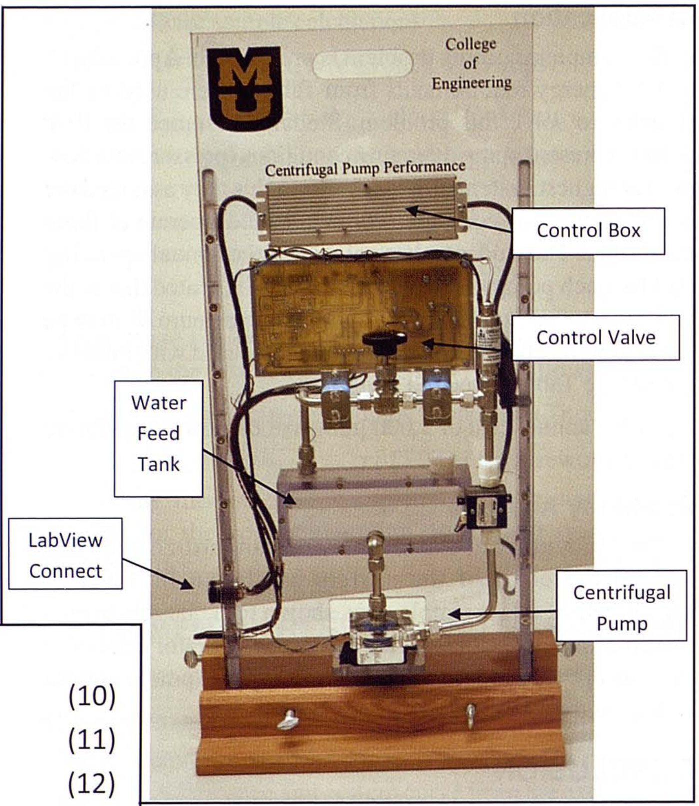


Figure 2 (above). *Photograph of the centrifugal pump experiment.*

Pump Performance Curves:

A (3540 rpm) $y = -1.3262x^2 + 0.5228 x + 29$ (10)

B (3330 rpm) $y = -1.3516x^2 - 0.3309x +25.01$ (11)

C (2610 rpm) $y = -1.4025x^2 - 0.282x + 15.002$ (12)

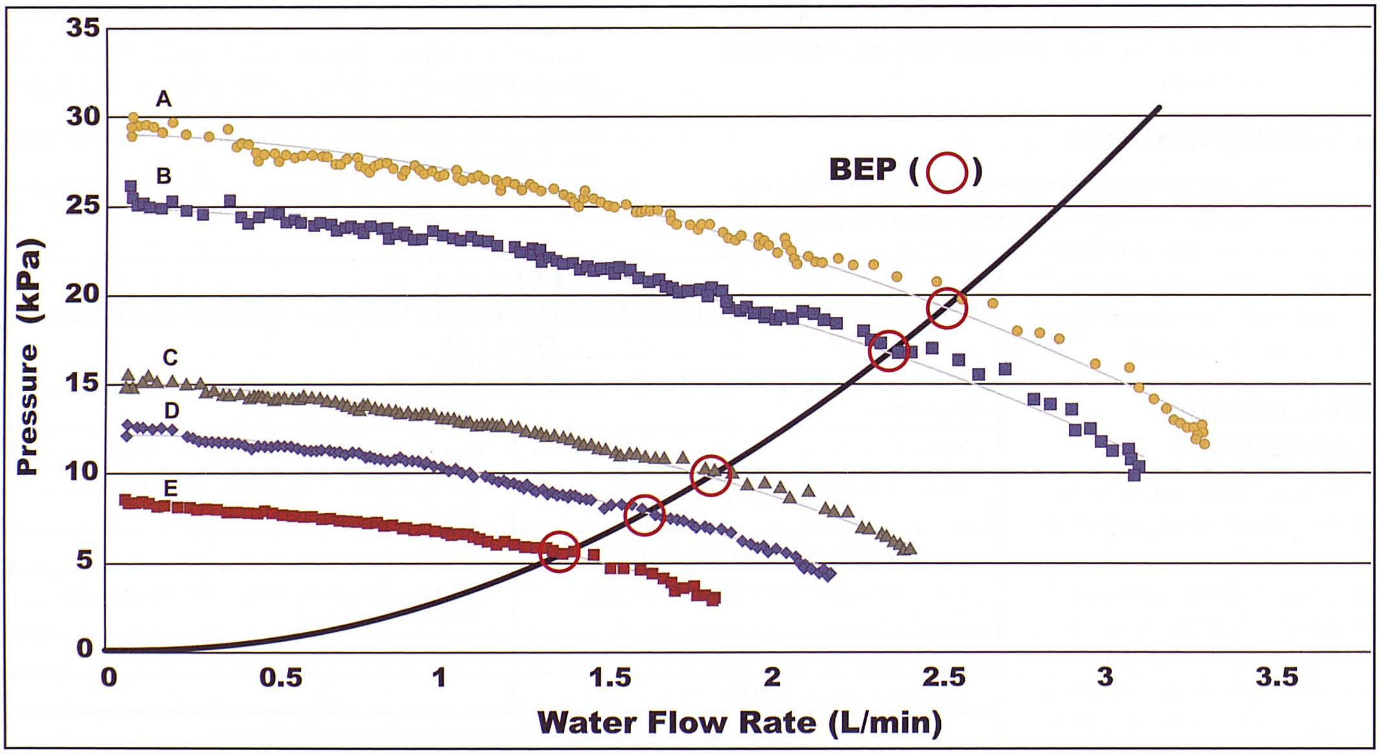
D (2340 rpm) $y = -1.3596x^2 - 0.6461x + 12.331$ (13)

E (2010 rpm) $y = -1.5414x^2 - 0.069x + 8.152$ (14)

System Curve: $y = 3.0156x^2 + 9x10^{-14} x - 5x10^{-13}$ (15)

where y = head (kPa) and x = water flow rate (L/min)

Figures 3 (left and below). *Best Efficient Point (BEP) at intersections of system curve and centrifugal pump performance curve(s) as function of impeller speed (rpm).*



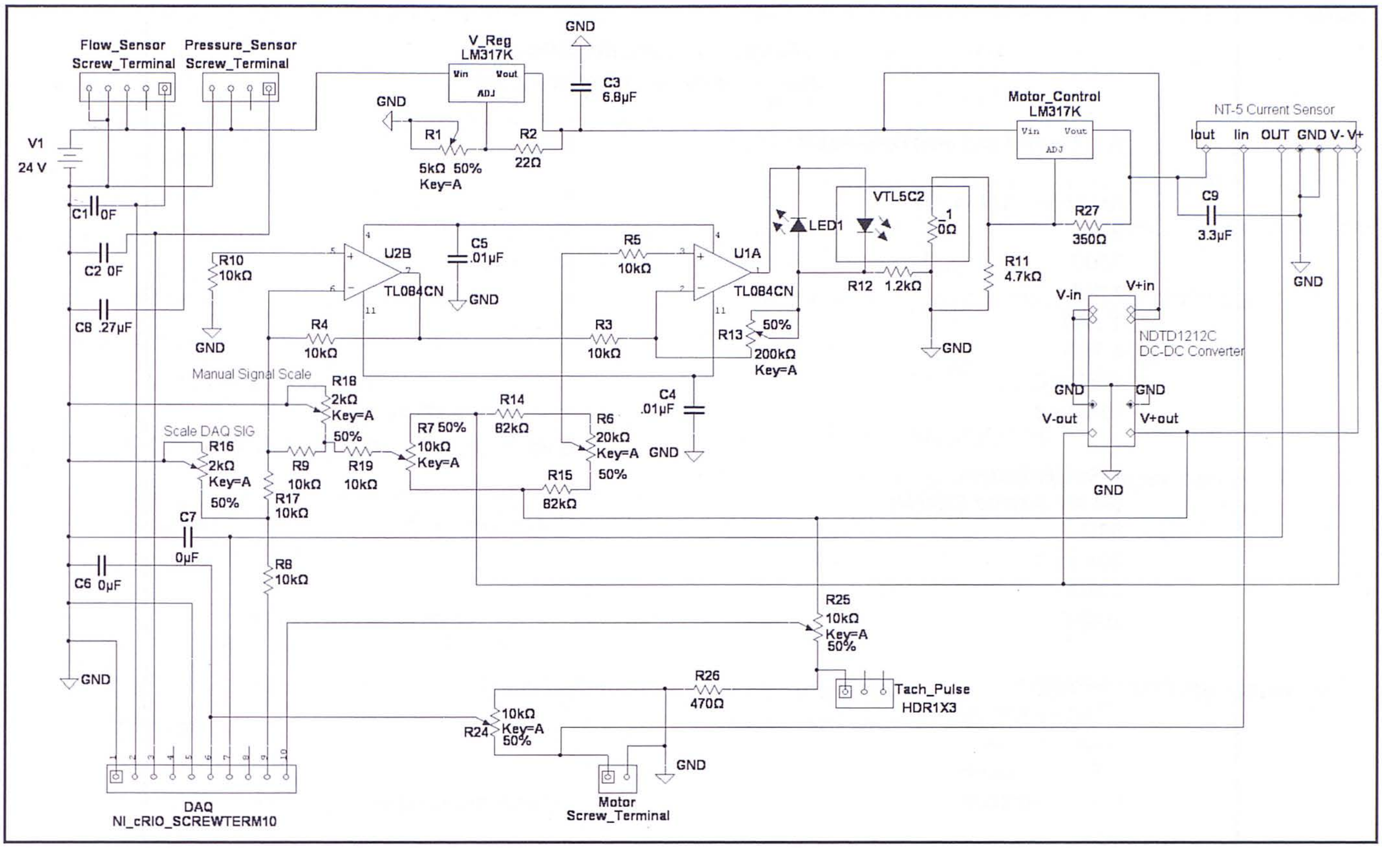


***Figure A-1**. Diagram of centrifugal pump system control and interface circuit.*

The dc-de converter is used to supply bipolar power to the op-amp IC in order for it to operate from OV. The 0-10V from labview transformed to 1.2-12V for the motor. A 2-stage opamp scheme includes:

- *1st for scaling, mixing signals (manual and data acquisition (DAQ)) and preliminary offset,*
- *2nd for LED in Resistive-optical-isolator (more offset and scaling plus some linearization)*

The offset can be used to approximate the OV DAQ output with the minimum voltage of the control regulator (1.2-1.7 V). The voltages going into motor starts at 6.8V and stops at 4.8V.

The scale factor of LabView voltage is not an issue due to the measuring of the voltage and current of the motor in Labview.

The tachometer has a voltage divider pull-up arrangement to match the counter input voltage to the DAQ.

Vreg1 (LM317K) is adjusted to a fixed value of l5V and is used as a pre-regulator. Vreg2 is used in adjustable mode implemented using the Resistive-optical-isolator. Non:-galvanic current sensor (NT-5) does not affect the operation of the circuit from which the current is being measured. It also provides no stray current paths. Capacitors on schematic with a value of OF are place holders for optional capacitors that were not used on the reference design.

Schematic

Figure A-1 presents a diagram of the centrifugal pump system control and interface circuit. A color version of the schematic can be found at <http://www.ornesengineering.com/schematic2.pdf>. The colored circuit schematic facilitates the design and verification of the system circuitry with the use of Multisim 11.0 in the Labview suite.

Parts Lists and Costs

A tabulation of the centrifugal pump lab costs and parts list is provided in Figure A-2 (page 56).

Total Cost of Parts: $893.75

APPENDIX B. CENTRIFUGAL PUMP LAB, OPERATING PROCEDURE

The procedure is available to students on Blackboard and readers at <http://www.ornesengineering.com/Procedure.pdf>.

APPENDIX C. SIMPLE APPLICATION FOR CENTRIFUGAL PUMP SYSTEM: COMPUTER COOLING

Determination of Pump Operating Conditions:

Data: One thousand computers must be cooled and CHE3243 lab data have been obtained. These data are the

Parts list for Centrifugal Pump
(Not including mounting structure)

A. Control and interface circuit

Resistors: (1/4 Watt)			
22Ω			
350Ω			
470Ω			
1.2KΩ			
4.7KΩ			
10KΩ x 8			
82KΩ x 2		$ .05 ea.	$.75
Potentiometers:			
(all are Bourne 3296W)			
5KΩ			
10KΩ x 3			
20KΩ			
200KΩ	(all 3296W's)	$4.00 ea	$24.00
Capacitors:			
.01μF x 2 ceramic			
.27μF ceramic			
3.3 μF Tantalum			
6.8 μF Tantalum		(Total all Capacitors)	$2.00
Solid State Parts:			
TL084CN x 2			
LM317K x 2		$5.00 ea.	$10.00
Misc. Parts:			
NDTD1212C			$11.00
NT-5 Current Sensor			$30.00
VTL5C2 optical isolator			$ 6.00
Mean Well 24V Switching Power Supply (CLG-100-24)			$80.00
LED (optional)			
3pin molex connector (for tachometer connector)			

B. Pump and transducers

Swiftech MCP355 centrifugal pump			$90.00
XSPC housing accessory for Pipe fittings			$90.00
Omega Flowsensor FLR1000			$255.00
Omegadyne PX-209-030-10V		$195.00	

C. Miscellaneous:

Valve, Fittings and tubing		$100.00	

Figure A-2. *Parts List and Cost for Centrifugal Pump Lab.*

basis for calculating the BEP (Best Efficient Point); the intersection of the pump characteristic curve and the system curve.

The 1,000 computers release 15,000,000 Btu/hr. The system friction losses are as follows:

Calculate the Pump (each) Flow Rate, Head, BHP, Efficiency, and Speed (RPM) for the BEP that requires the least annual cost for electrical power. The data for this task is included in Table C-1.

Assume commercial rate is 5 cents/kWh.

Assume pump operations are 8000 hr/year.

APPENDIX D. SAMPLE CALCULATIONS

Input data are from Figure 3 and Table 1. Values for annual energy used to calculate power cost are based on a July 2010 power cost for Columbia, MO.

Input Data

V = 6.5 V	Impeller Speed = 2010 RPM
I = 0.11015 A	Flow Rate = 1.35 L/min = 0.0000225 m^3/s

A) Input Power

$$P_{Input} = V * I$$

Where V is pump voltage and I is pump amperage

$$P_{Input} = 6.5\ V * 0.1015\ A = 0.66\ W$$

B) Output Power

$$P_{Output} = Q * P$$

Where Q is flow and P is the pressure

$$P_{Output} = 0.0000225\ m^3/s * 6.55\ kPa * 1000\ Pa/kPa = 0.147\ W$$

C) Efficiency

$$\text{Efficiency} = \frac{P_{Output}}{P_{Input}} * 100\%$$

$$\text{Efficiency} = \frac{0.147\ W}{0.66 W} * 100\% = 22.3\%$$

D) Determination of Local BEP

Pump Impeller speed = 2010 RPM

Pump Performance curve for selected speed:

$y=-1.5414x^2 + 0.069x + 8.152$

System Curve:

$y=3.0156x^2 + 9.0x10^{-14}x + 5x10^{-13}$

Solving the system of equation by Solver in Excel gives:

x=1.35 L/min y= 6.55 kPa

which corresponds to Table 1.

E) Annual Cost

Electrical cost was assumed at $0.0515/kWh.

Total Cost (Annual) = Number of Pumps * Operation Time * Cost of Power *P_{Input}

Total Cost (Annual) = 1000 pumps * 8000 hour

$$* \frac{\$0.0515}{kWh} * 0.66\ W * \frac{kW}{1000 W} = \$272/yr$$

Affinity Law Calculations

For the affinity law calculations input data is taken from Table 3.

Input Data

P_{max} = 29.57 kPa

N = 2130 RPM N_{max} = 4382 RPM

F) Standardization of Value by Affinity Laws for Constant Impeller Diameter

$$P_{std} = P_{max}\left(\frac{N}{N_{max}}\right)^2$$

where P_{max} is the maximum experimental pressure and N is the maximum impeller speed.

$$P_{std} = 29.57\ kPa \left(\frac{2130}{4382}\right)^2 = 6.99\ kPa$$

G) Percent Error

$$\text{Error \%} = \frac{Pstd - P\exp}{P\exp} * 100\%$$

$$\text{Error \%} = \frac{6.99 kPa - 6.22 kPa}{6.22 kPa} * 100\% = 12.32\%$$ ❒

TABLE C-1

System Data for Flow Rate vs. Pressure Drop

Water Flow Rate, lb/hr	Total Pressure Drop, psi
200	1.0
400	4.0
800	16.0

CHEMICAL ENGINEERING SCREENCASTS

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We previously reported the advantages of using screencasts in chemical engineering courses.[1] In the current paper we discuss uses of screencasts, describe their availability, present data that demonstrate how extensively they have been used, and provide additional student feedback. More than 430 screencasts have been prepared for seven chemical engineering courses: engineering calculations (computing), materials and energy balances, fluids, heat transfer, thermodynamics, kinetics/reactor design, and separations/mass transfer. Screencasts were prepared using Camtasia Studio 7 software,[2] which captures both narration and real-time screen input. These screen recordings were edited and processed into MP4 videos that are posted online.

Two aspects of these videos make them appealing: most are 10 minutes in length or shorter, and they are not of professional quality. Because they are short, they maintain students' interest, and they also do not take much of an instructor's time to prepare. A large number of short screencasts gives an instructor flexibility. They are like a living set of notes an instructor can add to and remove material from, case by case. They can be used to explain any learning activity. Because they are not professional quality, the instructor does not have to do multiple takes. Instead, they are similar to a class presentation of the same material. The feedback indicates that students in a number of classes use them frequently and are overwhelmingly positive about them.

Screencasts allow instructors to be more efficient; for example, they don't have to repeat the same explanation multiple times in office hours. Instead, they can refer a student to one or

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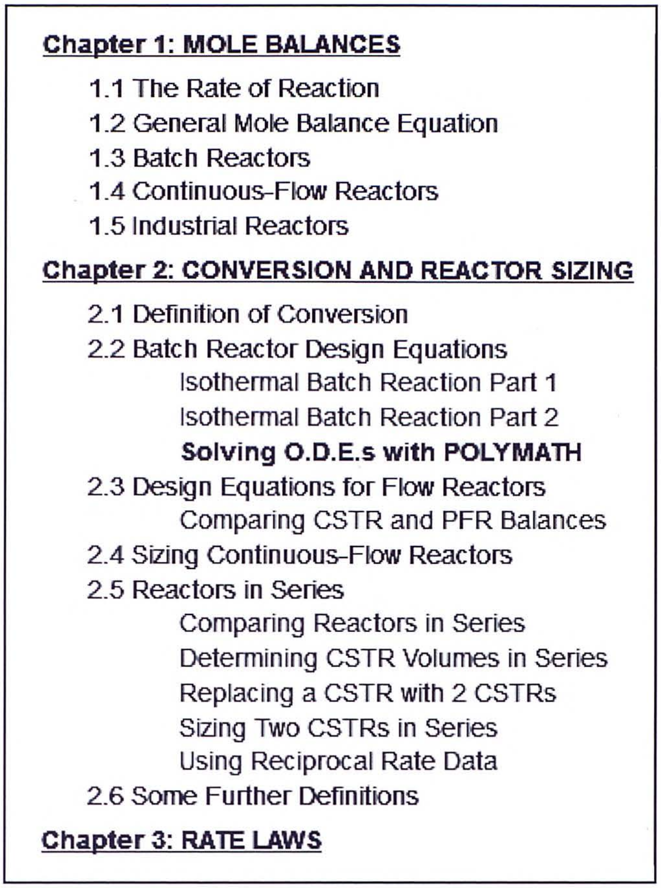
Janet deGrazia *is a senior instructor in the Chemical and Biological Engineering Department at the University of Colorado. She teaches a number of courses in the department including a course on technology for non-engineers. As chair of the Undergraduate Committee, her interests lie in curricular innovations and the use of technology in education. She received her Ph.D. from the University of Colorado in chemical engineering.*

Will Medlin *is an associate professor of Chemical and Biological Engineering and the ConocoPhillips Faculty Fellow at the University of Colorado. He teaches courses in kinetics, thermodynamics, and material and energy balances. His research interests are in the area of surface science and heterogeneous catalysis.*



Chapter 1: MOLE BALANCES

- 1.1 The Rate of Reaction
- 1.2 General Mole Balance Equation
- 1.3 Batch Reactors
- 1.4 Continuous-Flow Reactors
- 1.5 Industrial Reactors

Chapter 2: CONVERSION AND REACTOR SIZING

- 2.1 Definition of Conversion
- 2.2 Batch Reactor Design Equations
  - Isothermal Batch Reaction Part 1
  - Isothermal Batch Reaction Part 2
  - **Solving O.D.E.s with POLYMATH**
- 2.3 Design Equations for Flow Reactors
  - Comparing CSTR and PFR Balances
- 2.4 Sizing Continuous-Flow Reactors
- 2.5 Reactors in Series
  - Comparing Reactors in Series
  - Determining CSTR Volumes in Series
  - Replacing a CSTR with 2 CSTRs
  - Sizing Two CSTRs in Series
  - Using Reciprocal Rate Data
- 2.6 Some Further Definitions

Chapter 3: RATE LAWS

Figure 1. *Screenshot of* <www.learncheme.com> *website that show screencasts associated with the table of contents of Fogler's* Essentials of Chemical Reaction Engineering.*[16]*

more screencasts and ask him or her to return with questions. This allows an instructor to leverage his/her efforts by solving an example problem once and then referring the students to the video. Because the videos are short, they can be used as modules that provide a logical sequence for specific topics.

Previous studies have indicated the value of screencasts for improving student learning. Toto[3,4] used 60 screencasts in a general chemistry class for distance learners. His screencasts addressed concepts from homework assignments on which students scored poorly the year before. Students with access to the screencasts scored 11% better in the course overall and 22% better on the difficult concepts on which prior students scored poorly. In addition, the students overwhelmingly liked the screencasts. Similarly, Stelzer, et al.,[5-7] used web-based multimedia learning modules prior to class as an addition to, or even replacement for, the textbook. Student performance on questions assigned to be answered before class improved significantly when compared to those who did not have access to the videos.

The Khan Academy[8] is a library that contains more than 2,400 screencast videos covering math, science, and other topics. As explained on the website, "Each video is a digestible chunk, approximately 10 minutes long, and especially purposed for viewing on the computer." The website claims that more than 74 million lessons have been delivered. Pinder-Grover, at el.,[9,10] used screencasts in a large materials science course, using both qualitative and quantitative approaches to assess the effectiveness of their approach. They found that overall performance was positively linked to screencast usage. Garrigus[11] presented half of his lectures in the Texas public school system as screencasts, using the rest of the time for active learning. He found that class time was more efficient because he was able to engage the students in active learning and address individual student needs. Similarly, Bergmann and Sams pioneered a comparable approach, the "flipped classroom," which focuses on using screencasts instead of lectures.[12] In this model, video lectures are assigned before class, allowing the teachers to spend more time during class working directly with students. Their flipped classroom approach has been adopted in schools worldwide.[13]

Screencasts have also been used to train faculty and students to use educational technology. The Laurier Library[14] developed a site to instruct faculty in the production of screencasts, including resources to create them at their own universities. Western Kentucky University has prepared screencasts as video tutorials for campus training technology for Human Resources and the Faculty Center for Excellence in Teaching, adopting the model from Bowers, et al.[15] The University of Michigan library found that students who viewed instructional screencasts were able to not only complete a multi-step research process, but also able to apply concepts they learned to new situations.

CHEMICAL ENGINEERING SCREENCASTS

Available Screencasts

We have more than 430 screencasts posted on <*www.learncheme.com*> and on iTunesU and are continuing to add more. The thermodynamics and kinetics/reactor design courses have more than 120 screencasts each, and fluids and material and energy balances have more than 60. Screencasts are still being prepared for engineering calculations (computing), heat transfer, and separations/mass transfer; these courses have less than 30 screencasts each. The screencasts are organized by course topics and also by the tables of contents of commonly used textbooks for these courses. Figure 1 shows a screenshot from the website of part of the table of contents for Fogler's kinetics book.[16] Links to screencasts useful for a chapter section are listed under that section. A short text summary description of the screencast content is displayed when a mouse pointer moves over a screencast link. The screencasts are in MP4 format and can be watched online or downloaded onto computers, tablets, and smart phones. They can also be viewed in or downloaded to iTunes from iTunesU (search for University of Colorado).

Screencast Applications

The screencasts on <*www.learncheme.com*> include:

- *Example problems: most of the screencasts are solutions to numerical problems similar to those found at the end of textbook chapters. As we switched our instruction to more active learning, particularly using ConcepTests, student-held clickers, and peer instruction,*[17-21] *students requested more worked-out examples, and screencasts were prepared to address this request. These screencasts can be used to supplement or replace the example problems presented in conventional lecture-style courses.*
- *Exam reviews: for example, five screencasts that presented solutions to problems on previous final exams were made for review for a thermodynamics final exam instead of an evening exam review that has been used in the past. The class had 110 students, and each of these videos was watched almost 100 times. The students did better on the final exam than in previous years, so the screencasts were at least as effective as a live review.*
- *Software tutorials: screencasts are an effective way to explain the use of software.*
- *Explanations of how to use tables and graphs: for example, some screencasts explain how to use the steam tables to find properties of water, whereas others clarify phase diagrams or engineering charts.*
- *Explanations of confusing concepts or introductions to a topic: these are like mini-lectures.*

How Students Can Use Screencasts

Screencasts allow students to proceed at their pace so they can better understand the material, whereas instructors cannot go at a pace in class that is optimal for everyone. Students can also look at screencasts on their own schedule and they can play them more than once. They can stop and take notes and rewind; they can control the rate of information supplied to them. Thus, they have more control over their learning. Watching a screencast is more active than an in-class example.

Screencasts can be particularly useful for students who cannot attend office hours (*e.g.*, because of part-time jobs, extra-curricular activities, course conflicts) or students who need to refresh material from a prerequisite course. Students are sometimes poorly prepared for a course, especially when they took the prerequisite courses more than a year earlier. Screencasts provide a way for them to review at the beginning of the semester. Similarly, some graduate students do not have undergraduate degrees in chemical engineering, and screencasts might help prepare them for graduate classes. Some of our seniors take the Fundamentals of Engineering (FE) exam, which includes topics they may not have seen for two or three years. Screencasts are an effective way to reach a larger number of students than could attend a review session. Thus, screencasts are also organized by the topics in the FE exam on the website.

Student feedback

We have used screencasts for three years, in courses ranging from freshman chemistry to graduate-level kinetics, and the feedback has been overwhelmingly positive. Some typical anonymous comments at the end of the semester from students in a thermodynamics course in Fall 2010 were:

- *"Screencasts helped me understand concepts that I wasn't completely comfortable with."*
- *"The screencasts were the best thing that helped me learn in this course."*
- *"The screencasts help tremendously in providing good explanations."*
- *"The screencasts were extremely helpful for understanding material and preparing for exams."*
- *"The screencasts are also VERY helpful for homework and study. I use them a lot!"*
- *"Screencasts helped a LOT!"*
- *"I really like the screencasts; they help me learn the most."*

The responses to the question at the end of the Fall 2009 semester in thermodynamics, "How useful have you found the screencasts (videos) as a learning tool?" were also very positive, with 72% of the respondents saying they were useful or very useful. Feedback from 62 students in the Spring 2011 fluids course was similar: More than 91% of the students found them useful to very useful. The number of students who used the screencasts frequently (10 or more times) was high, and more than half the class claimed to have watched over half the screencasts.

One indication of the value of the screencasts is the number of times they have been played. We first posted screencasts online in August 2010 and gradually increased the number to more than 430. As shown in Figure 2, the number of

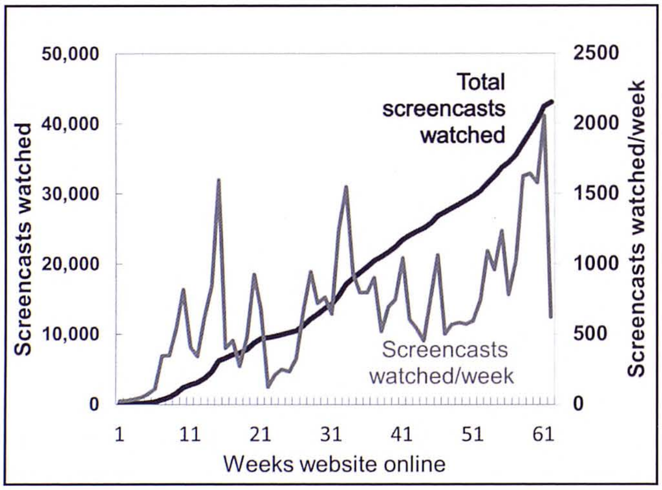


Figure 2. *Number of screencasts watched per week and total number of screencasts watched since initially posting screencasts online.*

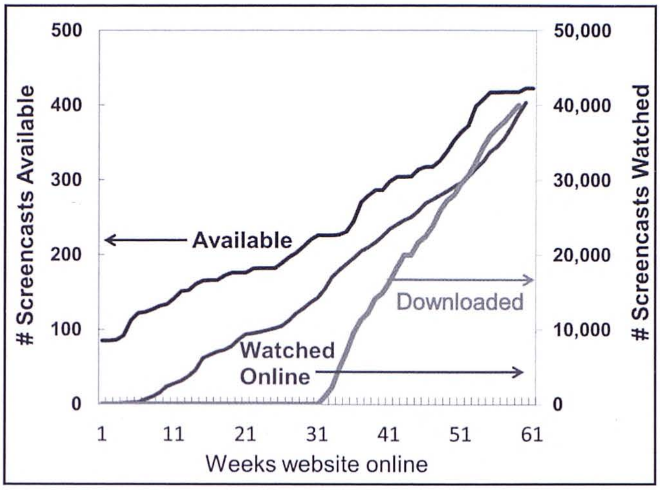


Figure 3. *Number of screencasts available online, watched and downloaded from both <www.learncheme.com> and iTunesU.*

screencasts watched each week varies widely, with some of the maxima corresponding to exams during the semester and to final exams. The screencasts have been played more than 43,000 times as of September 2011. In March 2011 (week 31 in Figure 2) the screencasts were also added to iTunesU, which allows them to be watched online or downloaded for offline use. As shown in Figure 3, in less than 28 weeks over 41,000 screencasts were downloaded, so that these screencasts were either watched or downloaded more than 84,000 times.

Planned Additions/Improvements to the Website

Screencasts are still being added to the website, with the goal of at least 75 screencasts for each of the courses. Biological engineering examples are also being added since most chemical engineering programs have a significant biological emphasis. We also plan to try an open forum in our courses to get feedback on aspects that are unclear or incorrect so that modified screencasts can be prepared.

PREPARING SCREENCASTS

An example problem solution presented in a screencast can potentially be more effective than a similar problem in a book. Detailed narration can be provided without a lot of preparation time. The screencast can emphasize what are known to be confusing aspects and point out common mistakes. It can also demonstrate a problem-solving format and demonstrate the types of solutions expected on homework assignments.

A 10-minute screencast of the solution to an example problem might take 30-40 minutes of the instructor's time to prepare, assuming the solution and calculations are already complete. An approach that we have found effective[22] includes the following:

- *Prepare a rehearsal script of exactly what will be included in the screencast. Include notes on points to emphasize.*
- *Start the screencast stating its purpose.*
- *Pause while recording to make the screencast shorter. Equations can be written, a diagram can be drawn, or numbers can be multiplied during the pause and the result explained when the recording restarts.*
- *Record the screencast as if presenting a problem solution in class, with all the attendant pauses, hesitations, dead times, and external noises.*
- *Follow a problem-solving outline: start with diagrams, label knowns and unknowns, use units throughout, make assumptions explicit, check solutions at the end, and so forth.*
- *Repeat a section if a mistake is made, rather than starting the recording over.*
- *Remove the errors and dead times after the recording is complete. This can be done by an undergraduate student assistant. Note that the dead times and other extraneous parts can be left in without compromising the screencast.*
- *Add highlights, annotations, and call-outs post-recording to focus a student's attention. This can be done by a B.S. level chemical engineer. These are not necessary, but highlighting can help minimize confusion, and call-outs can provide alternate explanations, definitions, or references to other materials.*
- *If the screencast looks like it will be longer than 10 minutes, break it into two screencasts.*

The cost for software and hardware to prepare screencasts is low. Tablet PCs cost less than $1,000 and Camtasia Studio 7,[2] which was used to record all screencasts on our website, costs less than $300. Other screen capture programs can be used,[23] but Camtasia is simple to learn, user-friendly, and has editing tools that can enhance the quality of the screencast.

SUMMARY

Over 430 screencasts have been prepared and disseminated online for seven core chemical engineering courses, and more are being added weekly. These screencasts are organized for each course by topic and also by textbooks' tables of contents. They have been played more than 43,000 times and downloaded 41,000 times. Student feedback has been extremely positive. Screencasts were prepared that present solutions to example problems, exam reviews, explanations on how to use software, and mini-lectures that introduce a topic or explain a concept. Suggestions were offered on how to produce screencasts. We encourage faculty to consider using the screencasts on <*www.learncheme.com*> as part of their courses or informing their students of the screencasts' availability so they can decide if the screencasts are useful.

ACKNOWLEDGMENTS

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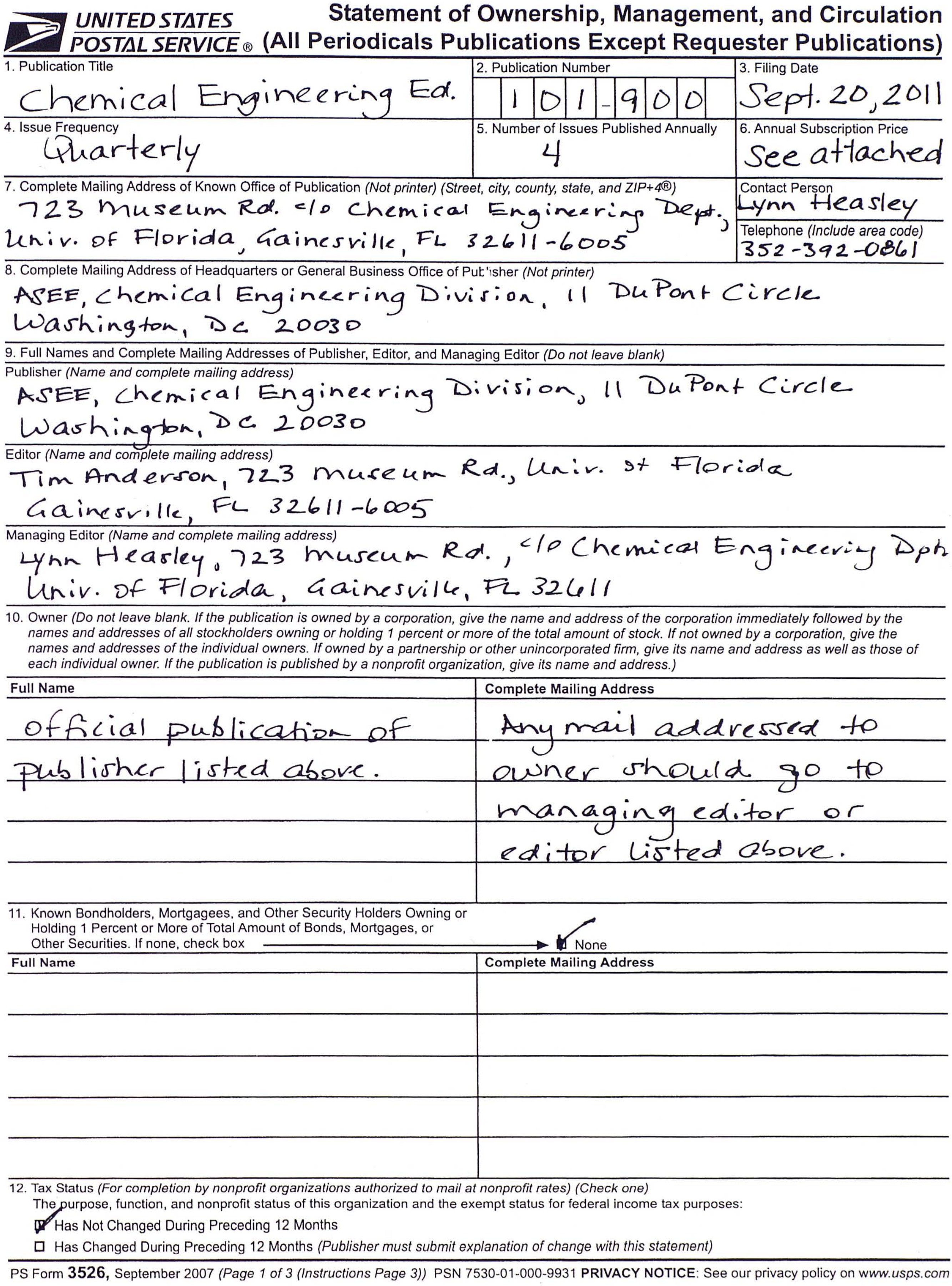

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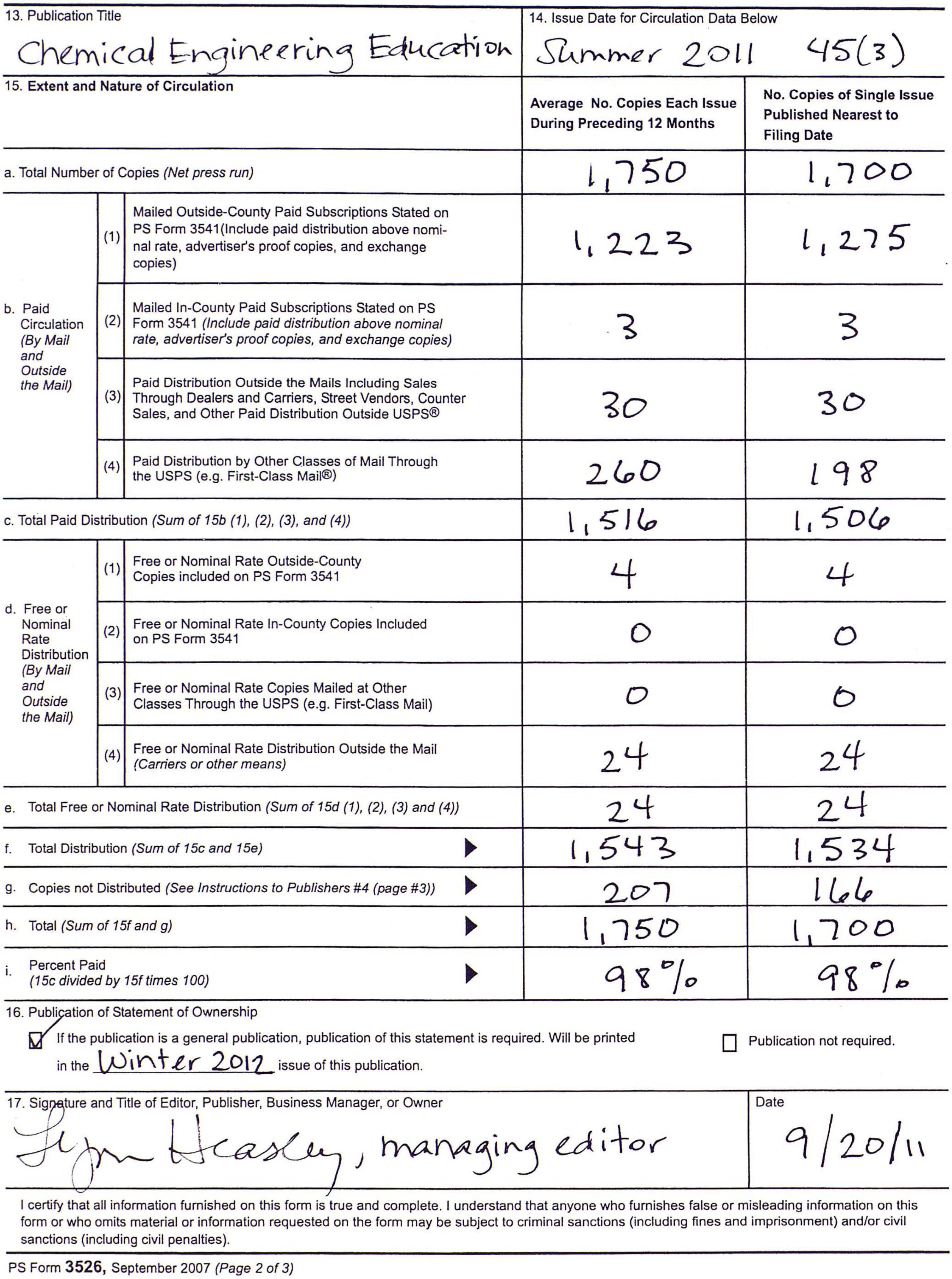

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