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Chemical Engineering Division of American Society for Engineering Education

DARSH WASAN

*of the
Illinois Institute of Technology*



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FAMU/FSU

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DARSH WASAN

*of the
Illinois Institute of Technology*

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*Illinois Institute of Technology
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"In his lectures, he's a spellbinder, an honest-to-goodness twentieth century Indian snake charmer,"

is how one former colleague describes Illinois Institute of Technology's Darsh Wasan. Professor Octave Levenspiel, now at Oregon State University, understands the students' enchantment. He says,

"Darsh is an exciting teacher because he is concerned with young people—his students—and he is in love with his subject. Research ideas bubble from him, and students flock to work with him. He works them hard, with evening and weekend conferences, but they love it. I'd say that close to half the students in the department did their theses with him."

Wasan's love for teaching and his ability to inspire his students were evident right from the start of his academic career. He came to the Illinois Institute of Technology in Chicago in 1964 after receiving his PhD from the University of California, Berkeley, and by the academic year 1966-67, all of his undergraduate and graduate classes had nominated him for the university's Excellence in Teaching Award, which he received that spring. In 1967 he was also promoted to associate professor and, in 1970 to full professor.

Through the years since then he has received numerous awards for teaching, including (in 1972) the American Society for Engineering Education's Western Electric Fund Award for Excellence in Instruction of Engineering Students.

Teaching and research seem so natural for Darsh, it is hard to imagine that he did not set out to become an educator, but at nineteen he thought he wanted to be a physician. One of eight children in his family, he had completed some pre-med courses and had

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even been accepted into a medical school in his native Bombay. But then his oldest brother, Madan (who was studying for his doctorate in mathematical statistics in the United States), proposed what proved to be an irresistible alternative for Darsh: chemical engineering. Madan had discussed his younger brother's math and chemistry talents with the admissions counselors at the University of Illinois Champaign/Urbana (UI), and they offered to admit Darsh to their undergraduate chemical engineering program.

Darsh turned out to have an aptitude *and* an enthusiasm for chemical engineering. At the UI he studied under Tom Hanratty, John Quinn, Jim Westwater, Daniel Perlmutter, and Max Peters (department chairman at that time). He did a senior-year project on fluid mixing under Quinn and during the summers served as an assistant in the research laboratories of Hanratty and Harold Johnstone. Intrigued with turbulent diffusion after a project under Hanratty, Darsh later chose this as his doctoral dissertation topic at Berkeley.

Harold Johnstone introduced him to colloids and interfaces. Wasan worked with Johnstone on an aerosol science project related to acid rain during 1959-60. The importance of interfacial and colloidal phenomena in chemical engineering processes and operations helped convince Wasan to focus his later research efforts in this area.

In August of 1960, after completing his undergraduate degree in chemical engineering, Wasan moved to California to enter graduate school. At Berkeley, he studied under Andy Acrivos, John Prausnitz, C. Judson King, Charlie Tobias, Eugene Petersen, Don Hanson, Charles Wilke, and Chang-Lin Tien (now Chancellor at Berkeley). While in grad school he began publishing, co-authoring two papers in turbulent transport ("Law of the Wall") with Tien, who was teaching mechanical engineering.

Wasan's doctoral thesis research under Wilke, in the field of mass and momentum transfer in turbulent flow, was the subject of the ASEE Chemical Engineering Division 3M Lecture that Wilke delivered at the 1964 annual meeting. Exactly twenty-seven years later, Wasan himself gave the 3M Award Lecture—this time on "Interfacial Transport Processes and Rheology: Structure and Dynamics of Thin Liquid Films."^{*}

In the summer of 1966, Wasan returned to Bombay and married Usha Kapur, a lovely and gracious woman with a degree in history and a flair for the culinary arts. They began their married life in a faculty apart-

Wasan's love for teaching and his ability to inspire his students were evident right from the start of his academic career . . . all of his graduate and undergraduate classes (have) nominated him for the university's Excellence in Teaching Award . . .

ment on the IIT campus, but after a few years and two sons (Ajay and Kern) they moved to a nearby suburb where they raised their sons (both now in college) and where they recently celebrated their twenty-fifth wedding anniversary. Both Darsh and Usha became naturalized citizens of the United States in 1974.

A Wasan tradition that his students and colleagues especially relish is the annual Indian feast that Usha prepares at the end of each summer. Darsh invites his research group of ten to twenty master's and doctoral students, as well as post-doctoral fellows and his professional colleagues, to share the good food, informal and genial conversation, and a spirited game of volleyball. Such occasions are only one of the ways Darsh encourages camaraderie among his students, many of whom regard him not only as an adviser but also as a friend and mentor.

In his twenty-eight years at IIT, Wasan has supervised about a hundred graduate students, including forty-five doctoral dissertations. Table 1 lists the names of his former PhD students and the professional colleagues with whom he shared some of them. Observations from his former students range from "He's always been more than just a professor to us; he genuinely cares about us," to "He has always been a very busy person—more so now that he has advanced in the IIT administration; but even now he always makes time for his students."

Many former students laud Wasan's ability to train his students in communication—in effectively presenting their ideas. Several remember Wasan's insistence on good presentations and good project proposal writing. "As an alumnus of his laboratory, I consider *that* as important as the research training I received under his tutelage," Raju Borwankar (a former student) says.

AS A RESEARCHER

Asked to comment on Wasan as a researcher, one of his close associates, Bill Krantz (University of Colorado), cites Wasan's prolific contributions to fundamental chemical engineering and credits him with "an exceptional ability to apply his research to

TABLE 1
PhD Students of Darsh Wasan

N. Aderangi	W. Jones	R. Ramakrishnan
R. Alexander	J. Kaellis	M. Ranade
B. Baker ¹	R. Kao	S. Randhava
R. Borwankar	M. Krawczyk	F. Rasouli ¹
J. Bouillard ¹	C. Lee ¹	J. Rosenfeld
C.W. Chi	L. Ting ³	J. Rudin
C.V. Chi ²	Y. Liu ¹	S. Shah
P. Chowdiah ¹	Y. Lo ¹	S. Sheth ²
S. Chung	L. Lobo	Y. Shih ¹
N. Djabbarah	A.K. Malhotra	S. Zheng ⁴
D. Edwards ³	H. Maru	S. Suneja
L. Gupta	V. Menon	F. Tavakoli ²
R. Gupta ¹	A. Mukherjee ¹	C. Thomas
D. Huang	J. Perl	M. Vora
U. Jayaswal ¹	A. Pintar	W. Wnek ¹

With • ¹D. Gidaspow ²R. Peck ³H. Brenner ⁴R. Beissinger

* Published in *Chem. Eng. Ed.*, 26, 104, (1992)

practical engineering problems."

Several industrial colleagues characterize Darsh as a man who has good intuition and who exploits it to the maximum. One commented, "He is the master of the scheme



Darsh and his colleague Dimitri Gidaspow examine computer model results for particle dispersion.

of things and decides to work on problems which he thinks are relevant. He always directs his efforts to real problems encountered by industry and does this research in collaboration and consultation with the related industrial scientific community."

One of the first academics to promote the concept of joint industry/university research programs, Darsh set up an Industrial Technical Advisory Committee in 1978 that has since been providing direction for his ongoing basic research program at IIT. Wasan himself describes his research philosophy simply as that of a true engineer. "I try to attack problems that *need* to be solved rather than choosing a problem that *can* be solved," he says.

Wasan's research activities span several separate but interrelated fields, focusing particularly on the importance of interfacial transport processes and rheology. This research has resulted in over two hundred and thirty publications, including seven research monographs, twelve book chapters, a textbook, and three U.S. patents.

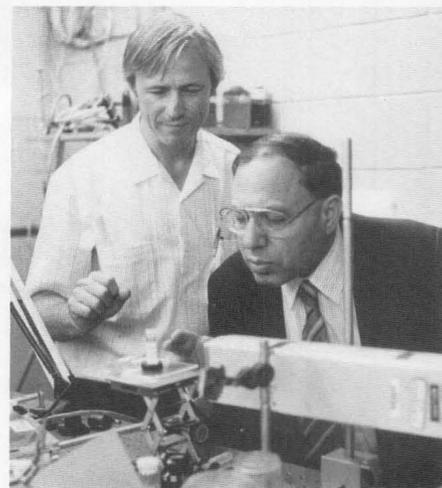
Darsh has maintained extremely good ties with industry and academic researchers in the U.S. and with researchers in Eastern Europe (especially Bulgaria), even in times when such collaborations were rare. Recognition of his collaborative work includes the Bulgarian Academy of Sciences' presentation of the Asen Zlatarov National Award in chemical sciences to Wasan and his collaborators for their research publications in thin liquid films.

His research contributions can be clustered into the following three areas:

Particle-Fluid Separation • Darsh and his colleagues were the first to simultaneously consider both hydrodynamic and molecular forces for the capture of small particles by fibrous and granular media, and the role of colloid chemistry in modeling deep-bed filtration, cross-flow electrofiltration, and lamella electrosettling for separating suspended particles from aqueous and non-aqueous media.

Synthetic liquid fuels derived from coal, shale, and tar sands contain particles of unreacted solids (ash-

carbonaceous residue) which impede downstream processing. The complex nature of colloid chemistry in non-aqueous media makes removal of these particles difficult. With sup-



Darsh and research associate Alex Nikolov examine microstructure formation in colloidal dispersions

port from the Amoco Corporation, the Department of Energy, and the National Science Foundation, Wasan and his IIT colleague Dimitri Gidaspow invented two practical devices based on electrokinetic phenomena (a cross-flow electrofilter and a lamella electrosettler) to separate colloidal particles from synthetic liquid fuels derived from coal, shale, and tar sands. These methods, significantly more energy-efficient than conventional techniques, have applications in upgrading other synthetic crudes, heavy residual oils, fluid catalytic cracking slurry oil, hydraulic oil, and other organic liquid slurries.

In 1986 the National Science Foundation awarded Wasan and Gidaspow a Special Creativity Award for their work on electrokinetic phenomena in non-aqueous media. More recently, their research group has been developing a dry electrostatic process for separating a powder mixture into its components based on their work functions, and they have successfully applied their new method to mineral beneficiation.

Interfacial Rheology and Thin Liquid Surfactant Films • Many separation processes utilize surfactants, *i.e.*, substances which are interfacially active. In 1988, Wasan edited the first book on surfactants—*Surfactants in Chemical/Process Engineering*. His quest to develop new instruments for measuring dynamic properties of fluid-fluid interfaces containing surfactants and the dynamic behavior of thin liquid films formed from surfactant solutions put him at the frontier of dispersion science and

Chemical Engineering Education

Wasan's research was the first to identify the significant role of the coalescence phenomenon in the oil bank formation and propagation rate processes in porous media and the stability of emulsions in optimizing oil recovery in both conventional and enhanced oil recovery processes.



Wasan's present research team.

technology, contributing to advances in areas such as emulsification/demulsification, foaming/anti-foaming, wetting, surfactant liquid membranes, and enhanced oil recovery.

Noting that the field of interfacial rheology (and its application to emulsion stability, thin film drainage and rupture, and enhanced oil recovery by surfactant/polymer processes) has developed as a science largely in the past twenty years, Bob Schechter (University of Texas) credits Wasan and his students for a significant part of this recent progress. He cites the Wasan team's development of precise, reproducible, and meaningful methods for measuring interfacial viscoelastic properties. "His work significantly improved the deep channel surface viscometer, and his group has published more comprehensive studies than any other group," Schechter notes.

A commercial version of Wasan's interfacial shear viscometer is now used worldwide as the primary tool in emulsion and foam stability research. A second instrument for measuring dynamic interfacial tension (an expanding drop tensiometer) is under development.

After developing reliable measurement techniques, Wasan published a series of papers clarifying the role of surface viscosity and elasticity in stabilizing thin liquid surfactant films. These studies, fundamental to an appreciation of both foam and emulsion stability, provided the theoretical groundwork whereby

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interfacial rheological considerations can be included in coalescence phenomena and interfacial mass transfer processes. Consequently, industry now recognizes the potential influence of interfacial rheological behavior in the design of many engineering processes involving dynamic fluid-fluid interfaces in dispersed multiphase systems, such as suspension and emulsion polymerization processes. Wasan summarizes this work in his recent textbook, *Interfacial Transport Processes and Rheology*, written with his former doctoral student, David Edwards, and Professor Howard Brenner.

In 1986, Darsh and his colleagues discovered a new mechanism for the film stability induced by the formation of "ordered" surfactant micelle structures inside the film over distances of the order of 100nm or 1000Å and ushered in a new era of research on understanding the nature of interactions within supermolecular fluids such as concentrated suspensions of Brownian particles, surfactant micellar solutions, and microemulsions. They showed that the phenomenon of multilayer structuring or stratification (*i.e.*, internal layering of micelles) in thinning liquid films is much more universal than previously thought. Stratification can also be observed in concentrated submicron particle suspensions such as those of polystyrene latexes and silica hydrosols with narrow size distribution and prevailing repulsive forces. The formation of long-range ordered structures inside thin films has many implications of both fundamental and practical significance—for example, the dynamic process of stratification in submicron thin liquid films can serve as an important tool for probing the long-range structural or interaction forces in concentrated particle suspensions and colloidal dispersions. The rheology of dispersions containing stratifying films is quite different.

In 1988, when NSF recognized Wasan's discovery of "ordered microstructures in thin liquid films" of concentrated colloidal dispersions with another Special Creativity Award, he became the first engineering scientist to receive the award twice.

Enhanced Oil Recovery • After the oil embargo of 1973, Darsh was one of the first academics to embark on a basic research program aimed at improving oil recovery. He sought understanding of the fundamental mechanisms by which the oil is displaced in porous media for successful applications of

surfactants/alkali, and foam processes. This program, initiated and funded under the auspices of NSF-RANN (Research Applied to National Needs), has also received financial support for the Department of Energy and industrial sources.

Wasan's research was the first to identify the significant role of the coalescence phenomenon in the oil bank formation and propagation rate processes in porous media and the stability of emulsions in optimizing oil recovery in both conventional and enhanced oil recovery processes. This basic research program was also the first to elucidate the effect of the presence of oil on foam performance. Wasan discovered the importance of "pseudoemulsion" film (*i.e.*, water film between the oil and gas), which had not previously been recognized, in controlling the foam stability. His pioneering use of differential interference microscopy to investigate film stability, contact angles, and wetting and spreading phenomena, has now been adopted by industry.

In 1978, Wasan's research on "Improved Oil Recovery" was one of the three research programs featured in the Annual Report of the NSF to President Jimmy Carter. This research was selected from 834 NSF grants in force at the time in the Engineering Division of NSF.

In 1989, the Chicago Section of the American Institute of Chemical Engineers presented Darsh with the Ernest W. Thiele Award for outstanding contributions through the practice of chemical engineering. He was cited for his "innovative research in particulate separations, petroleum recovery, and interfacial phenomena as well as his contributions as an inspiring teacher and dynamic leader of IIT."

WASAN AS AN ADMINISTRATOR

Wasan's contributions to engineering education not only include award-winning teaching and research accomplishments, but also academic leadership as IIT's chemical engineering department head (1971-77, 1978-87), College of Engineering dean (acting, 1977-78 and 1987-88), vice president for Research and Technology at IIT and IIT Research Institute (1988-91). In 1991 President Lewis Collens tapped Darsh for the post of provost, noting that "Darsh will bring great energy, enthusiasm, and insight to the process of creating a new IIT for the 21st Century."

A former colleague, Larry Tavlarides, credits Darsh with a "strong and positive influence in the growth and stature of the chemical engineering department at IIT during the decade of the seventies and on a cadre of faculty who grew professionally during that period." He notes that "the group included those of

us who moved on: Jim Vrentas, Herb Weinstein, Tom Fitzgerald, and me," and adds that, "Those who remained are among the pillars of the current department: Dimitri Gidaspow and Rob Selman. It took an enormous amount of skill, sincerity, and good will so that we could all grow in stature in a harmonious way."

As a long-term department chairman, Wasan was responsible for keeping both the graduate and undergraduate curricula relevant for the changing needs of society. He did this by establishing an Industrial Advisory Council for the department and appointing such distinguished chemical engineers and IIT alumni as Jim Oldshue and John Sachs, who are both former presidents of AIChE. He also established premier laboratories in the department for undergraduate teaching and graduate research.

As acting dean of IIT's Armour College of Engineering, he recruited an engineering faculty recognized for its excellence and developed cross-disciplinary specialized minors (which generally consist of five courses) to enhance students' professional breadth and potential for advancement.

As vice president for research and technology, Wasan was the motivating force behind the creation of the National Center for Food Safety and Technology, housed at IIT's Moffett Campus. This unique center brings together academia, industry, and government to do research in new food processing and packaging technologies, with the goal of increasing consumer food safety. Established in 1989 with a gift from CPC International, Inc., of a five-building, seven-acre facility including an industrial-scale pilot plant, the center was initially funded with a \$3.7 million cooperative agreement between IIT and the U.S. Food and Drug Administration (FDA). That agreement, recently renewed at \$2 million per year, supplements funding from fifty leading food-industry related member-companies. Today, research at the Center is being conducted by forty scientists from the FDA, faculty from both IIT and the Department of Food Science at the University of Illinois at Urbana-Champaign, scientists from IIT Research Institute, and from the member companies.

As provost, Wasan quickly took a bold step, crossing traditional boundaries between engineering and science at IIT—he moved the departments of biology, chemistry, computer science, mathematics, and physics out of the College of Liberal Arts and Science into a new, combined College of Engineering and Science. His goal in this realignment was to bring an interdisciplinary focus to engineering and science education at IIT. To that end, he encouraged the environmental

engineering department to add an environmental engineering baccalaureate program that builds on the strengths of its graduate program, and initiated several five-year, double-degree (BS and MS) interdisciplinary programs, including medical engineering, computer systems engineering, manufacturing engineering, food safety and technology, and environmental engineering.

He has also embarked on a university-wide campaign to revamp undergraduate curricula to prepare students for significant careers in the 21st Century. Quality, creativity, ethics, and leadership will be taught across the curriculum. He is working closely with advisers from Motorola University to introduce these four critical elements and strengthen the development of students' communications skills throughout the curricula. "We are in a sense redefining and sharpening the tradition of a liberal arts education in the context of an institution focused on technology and the professions," says IIT President Collens.

Wasan is also developing a new undergraduate internship program with industry. The goal of the program is more than just hands-on experience. Educational objectives are to be set for each internship period, and companies are being asked to identify appropriate employees to serve as mentors to the interns. Ultimately, the mentor will determine the educational objectives in cooperation with the intern's faculty adviser, and work with the faculty adviser in evaluating the student's performance.

SERVICE TO THE PROFESSION

Wasan's zeal for chemical engineering education and research extends to scientific communication in general and to the institutions that facilitate it. He has chaired the ASEE Publications Board of *Chemical Engineering Education*, the technical program of the AIChE's 69th Annual Meeting, and the Interfacial Phenomena and Transport Processes research committees of the AIChE. In addition, he served on the AIChE Education and Accreditation Committee and Ad Hoc Visiting Committee of ABET and was president of the Fine Particle Society. In 1986 he and Bill Krantz organized an NSF Workshop on Interfacial Phenomena in New and Emerging Technologies.

Wasan has chaired some forty research symposia at various national and international meetings and, over the years, has delivered more than one hundred lectures and seminars in academia and industry. He has served as: a member of the Engineering Advisory Committee for the Chemical and Process Engineering Division at NSF; member of the advisory committees for the Department of Energy's Oak Ridge Na-

tional Laboratory Chemical Technology Division and National Institute for Petroleum and Energy Research in Bartlesville, Oklahoma; member of the review committee for the Argonne National Laboratory Energy System Division; member of the Executive Committee of the Governor's Science Advisory Committee for the State of Illinois; consultant to the United Nations Development Program in India. In addition, he has served as a consultant to several industries, including Exxon Research and Engineering Co., Stauffer Chemical Co., American Cyanamid, ICI of America, and Nelson Industries.

In recognition of all his accomplishments, ASEE gave him the 1991 Chemical Engineering Division 3M Lectureship Award. The official citation reads, in part:

The 3M Lectureship Award is presented to Darsh T. Wasan for his outstanding contributions to the field of chemical engineering. As a teacher, he has been an inspiring and enthusiastic instructor, helpful to students inside and outside the classroom. As a researcher, he has been creative, innovative and has been a pioneer in advancing the frontiers of knowledge on interfacial phenomena and utilizing this knowledge to solve energy and environmental problems. As an administrator, he has contributed to the drive for excellence of his department, the College of Engineering, and IIT as a whole. As a professional engineer, he has contributed to the solutions of industrial problems as a consultant to industry as well as promoted the growth of knowledge by organizing current state-of-the-art symposia at professional meetings and by identifying the future directions of research.

In summarizing Wasan's contributions to education, research, academic administration, the profession, and collaborative efforts, many of his friends and colleagues are struck with the exceptional balance that he has maintained throughout his academic career. Cynthia Hirtzel, in presenting Wasan with the Donald Gage Stevens Distinguished Lectureship Award of Syracuse University in 1991, expressed what many of Darsh's friends feel when she said, "When I think of Wasan, many adjectives—mostly superlatives—come to mind. One quality which will always be foremost in my mental picture of him is his phenomenal energy. His energy for his work, for education, for research, for his students and colleagues, is prodigious and almost intimidating to those of us who would strive to emulate his examples. It is truly a privilege and a joy to know him."

ACKNOWLEDGMENT

A number of Darsh's colleagues and former students contributed significantly to the preparation of this article, and their kind and generous contributions are very much appreciated. □

FAMU/FSU



Central atrium (above) and laboratory wing (right) of the FAMU/FSU College of Engineering

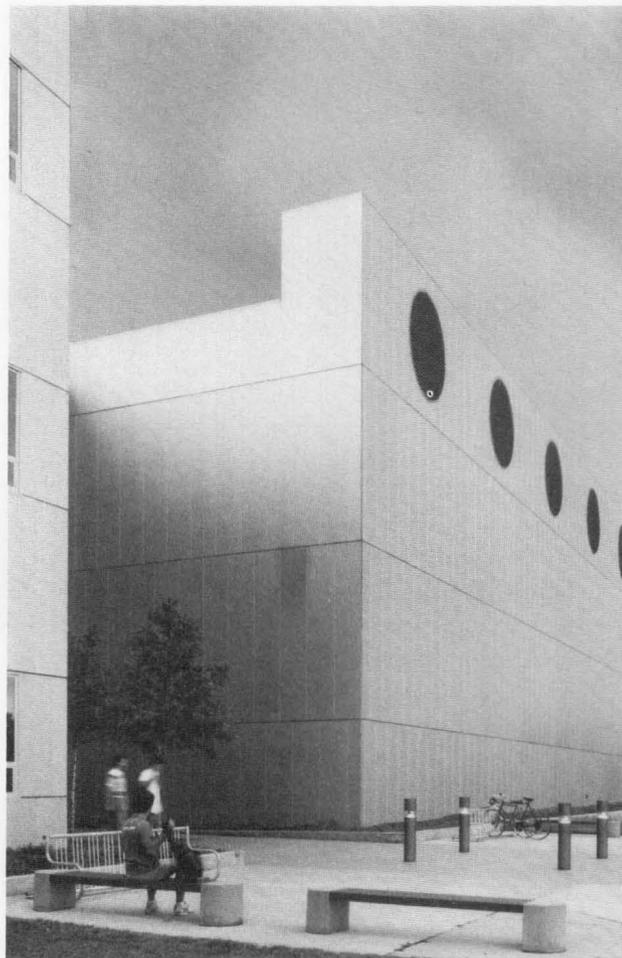
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*FAMU/FSU College of Engineering
Tallahassee, FL 32316-2175*

The Chemical Engineering Department at the FAMU/FSU College of Engineering is part of a unique program that developed through collaboration between Florida Agricultural and Mechanical University (FAMU), a historically black university, and the Florida State University (FSU), formerly the Florida State College of Women.

FAMU was chartered in 1887 and has traditionally focused on a strong undergraduate education in basic studies, business, engineering technology, and agriculture. It currently enrolls about 9,000 students from a wide geographical area.

The roots of FSU go back to 1851, although it was not until 1947 that the State Legislature granted it university status. Total current enrollment is about 28,000 and includes students from most states in addition to 105 foreign countries. There are approximately 4,500 graduate students at FSU.

Although the College of Engineering is young (it was authorized by the 1982 Florida State Legislature), it has experienced an extraordinary rate of growth. Student en-



rollment has increased by an average of fifteen percent per year over the last three years. ABET-accredited undergraduate degrees are offered in all departments: chemical, civil, electrical, industrial, and mechanical engineering. MS degrees are offered in all of the disciplines except industrial engineering, and PhD degrees are offered in chemical and mechanical engineering. The college currently enrolls over 1800 undergraduate students and 200 graduate students. It has approximately seventy full-time professors.

Engineering students can enroll at either FAMU or FSU. They must, however, satisfy both the general education requirements of the school in which they are enrolled and the specific requirements of the Engineering College. All engineering classes are taken at a single engineering complex, which is convenient to both campuses, while courses in basic studies, sciences, and mathematics are taken at the student's respective university. The degree is granted by the College of Engineering through the university where the student is enrolled.

Although nationally recognized as a major football powerhouse, FSU has traditionally also had strong programs in liberal arts and the basic sciences. With the appointment of a new university president (Dr. Dale Lick, a mathematician), along with the development of the National High Magnetic Field Laboratory and the Supercomputer Computations Research Institute, the expansion of the centers for Materials Research and Structural Biology, and the high quality of the physics, chemistry, biology, geophysics, and applied mathematics departments, FSU is poised to become one of the nation's top research and educational institutions. It is currently ranked among the top colleges by college-bound high school seniors as a desirable place to study.

The home of the internationally known "Marching 100," FAMU is ranked high by college-bound minority students as an attractive place for pursuing higher education. Through the active recruitment efforts of its president (Dr. Frederick Humphries, a physical chemist by training), FAMU currently attracts a large number of highly qualified minority students who are eager to major in chemical engineering. Several FAMU students presently hold full "life gets better" scholarships, supported by industry, which provide full financial assistance for obtaining a bachelors degree as well as providing summer internships.

THE CHE DEPARTMENT

Fifty-five bachelors degrees, five masters degrees, and two doctorate degrees have been granted by the Chemical Engineering Department as of fall, 1992, and current enrollment includes approximately 250 undergraduate and 15 graduate students. Research and graduate-level activities began soon after the department was founded, and the PhD program was fully approved by the Board of Regents in the fall of 1989. The department has embarked on a new five-year strategic plan emphasizing research and education in newly developing areas of chemical engineering science and technology.

Undergraduate Program

The department is committed to providing a high quality and "modern" education in the basic principles and practices of the chemical engineering profession. In addition to maintaining a strong curriculum which incorporates the fundamentals of chemical engineering, the faculty believes that it is important to incorporate applications from the emerging areas of chemical engineering into the core courses. These include biotechnology and biomedicine, advanced materials (polymers, ceramics, and composites), computer-assisted process and control engineering, and surfaces, interfaces, and microstructures.^[1-3] Also, because of the rapid changes and added complexities in the profession, greater emphasis is being placed on occupational health and safety practices in laboratories, environmental protection, waste minimization, and recycling. In addition, elective courses in bio^[4] engineering, polymers, chemical-environmental engineering, advanced materials science and engineering, molecular engineering, and macromolecular transport^[5] provide, in part, a more comprehensive study of the emerging areas in chemical engineering.

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A familiar student gathering in the atrium.

As part of its growth plan, the department is currently adding modern developments to the undergraduate curriculum, including new developments in molecular structure, state-of-the-art instrumentation and experimental techniques, statistical methods and their rational application to process design (including design of experiments), and quality control.

All qualified undergraduates are strongly encouraged to participate in research projects through both the Honors Program and Directed Individual Studies. The Honors Program emphasizes research with faculty for the highly talented and motivated student.

The nationally accredited student AIChE chapter is an active group that sponsors a number of plant trips to local industries, arranges and schedules talks by professional engineers, and publishes a newsletter, *The Innovator*, twice a year that contains articles by both students and faculty. In addition, the student chapter is the focal point for information on graduate school opportunities and also schedules talks from visiting academicians on graduate research and education in chemical engineering.

The department awarded approximately \$15,000 of industrially supported scholarships to the top undergraduate students in the 1991-1992 school year.

Graduate Program

The department offers both a thesis and a non-thesis option leading to the Master of Science degree. The core curriculum required for both options includes advanced chemical engineering thermodynamics, transport phenomena, reactor design, and mathematical analysis, in conjunction with proficiency in computational skills such as numerical solution of engineering problems.

PhD students have the option of selecting graduate courses from a variety of choices that includes, among others, applied mathematics, advanced transport phenomena, macromolecular transport, statistical mechanics, polymer rheology, and compu-

PhD students have the option of selecting graduate courses from a variety of choices that includes . . . applied mathematics, advanced transport phenomena, macromolecular transport, statistical mechanics, polymer rheology, and computational techniques.

tational techniques. A wide range of other advanced courses is available in the departments of chemistry, physics, biology, applied mathematics, and mechanical engineering.

The department is strongly committed to building a solid graduate research program in both applied and fundamental areas. The faculty believes that graduate programs must be diverse, interdisciplinary, and flexible in order to prepare chemical engineers to handle the applications of a quickly changing technology.

FACULTY RESEARCH INTERESTS

Faculty members are actively involved in several areas, including polymer processing, biochemical engineering, materials research, semiconductor processing, macromolecular dynamics, reaction kinetics, molecular transport phenomena, expert systems, thermodynamics, and applied and computational mathematics. Many of these efforts are conducted in close cooperation with the Florida State University Supercomputer Computations Research Institute (SCRI), the Material Research and Technology Center (MARTECH), and the departments of chemistry, physics, biology and applied mathematics at FSU. Currently the department has seven full-time faculty members, one adjunct teaching professor, and four affiliate professors.

Pedro Arce joined the department in 1990 after completing his Masters and PhD at Purdue under

the direction of D. Ramkrishna. He also has several years experience in teaching and research at the Universidad Nacional del Litoral (Sante Fe, Argentina). His research revolves around a variety of problems in material design synthesis and processing, with a strong emphasis on the application of fundamental principles, advanced mathematical methods, and physical theory closely coupled with computational techniques and experiments. The central theme of his investigation is an understanding of basic transport phenomena and physicochemical aspects involved in, for example, crystal growth, ceramics technology, polymeric gel media, and composite fluids. In the modeling approach, Dr. Arce uses advanced mathematical techniques such as operator-theoretic and group-theoretic methods, bifurcation theory, and asymptotic techniques in conjunction with the application of computer-aided functional analysis. In regard to complex and composite fluids, his objective is to study the nature of, and the role played by, the interparticle forces in order to yield models capable of predicting interfacial behavior, suspension stability, and "ordering" under the applied field. Hydrodynamic theories, statistical mechanics treatment of the microstructure, fractal theories, and computer-aided analysis are the main tools of this research. Dr. Arce also has an interest in active-learning techniques. For example, his efforts have led to the development of a technique called the "colloquial approach."^{16]}

Ravindran Chella joined the department in 1986 after doing postdoctoral work at the University of Pittsburgh. He obtained his PhD from the University of Massachusetts under the supervision of Julio M. Ottino. He also has a Master of Science Degree in Chemical Engineering from Rutgers University. His current research interests are primarily in the characterization of composites and polymer processing. He is also a member of MARTECH and much of his research is in collaboration with colleagues in the department of mechanical engineering. Moire interferometry is being used for the thermo-mechanical characterization of polymer and metal matrix composites. Boundary element methods are being used for stress analysis and characterization of composites under thermo-mechanical loading. The computational work is coordinated with experimental microstrain measurements, and numerical algorithms are being formulated to take advantage of the extensive facilities available at SCRI for vectorized and parallel computing, including a Cray Y-MP super-computer and a 64-K node Connection Machine. This is important for simulations involving complex geometries and nonlinear material be-

havior. In the area of polymer processing, laser-speckle techniques are being developed to obtain instantaneous velocity distributions over a plane in prototype two- and three-dimensional polymer processing flows relevant to extrusion and coextrusion. Experimental results are used in the verification and refinement of finite-element and boundary-integral models of the flow.

David Edelson, a graduate in physical chemistry from Yale University, joined the department after a number of years spent in research at AT&T Bell Laboratories. His research interests are in the areas of chemical kinetics and reactive flows, and in the use of computation simulation and the development of expert systems for the elucidation of mechanism, identification of controlling processes, and prediction of the behavior of reactive systems. Dr. Edelson is also a faculty associate with SCRI, and together with colleagues in computer science, has been engaged in the prototype design of an expert system for the simulation of reactive flows.

Bruce Locke was hired as an assistant professor in 1989. He completed his Masters at the University of Houston under the supervision of Neal Amundson and earned his PhD at North Carolina State University under the direction of Ruben Carbonell. With strong backgrounds in both mathematical modeling methods and experimental development, Dr. Locke's general research interests are in combining experiments with fundamental principles in order to understand and improve a wide range of processes and phenomena. Combining four years of experience at the Research Triangle Institute (in North Carolina) in the area of aerosol physics and fine particle studies with work on macromolecular separation processes at North Carolina State, he now focuses on research in particle and macromolecular transport processes. Dr. Locke, in collaboration with Dr. Arce and colleagues in the departments of physics, chemistry, and biology at FSU, is seeking to improve the separation of large DNA molecules using pulsed field electrophoresis. He also has an underlying and continuing interest in applying chemical and biochemical engineering fundamentals to solving environmental problems. As part of this environmental interest, Drs. Locke and Arce are analyzing the combined reaction and transport processes occurring in pulse streamer coronas in order to improve design and operation strategies for air and water pollution treatment.

Srinivas Palanki joined the department in 1992 after completing his PhD at the University of Michigan under the supervision of Costas Kravaris and

FAMU/FSU enjoys a unique multicultural atmosphere that is fostering development of a first-class chemical engineering department. [The new dean], Dr. C.J. Chen, . . . is actively working on important projects for the future.

Henry Wang. As a graduate student he also spent a year at Merck and Co., Inc., working on optimization and scale-up of antibiotic fermentations. His primary research interest is in optimization and control of batch reactors with applications to biological processes. Since batch reactors do not have a process steady state, there are no conventional "steady-state set points" to which a conventional controller can be tuned. The major objective is to minimize an objective function at the end of the batch cycle. Due to batch-to-batch variations in complex processes such as biological fermentations, an *a priori* calculated operating scheme may lead to suboptimal performance. Using "geometric tools," Dr. Palanki is developing feedback laws for end-point optimization of batch reactors. This approach attenuates uncertainties and disturbances to the batch process and is independent of initial conditions. Coupled with state and parameter estimation algorithms, this approach provides the basis of an on-line adaptive optimization scheme. Dr. Palanki also has a strong interest in developing techniques for understanding and tracking key intracellular events which control the production of chemical of interest in batch fermentations and using these methods for optimal design and scale-up of batch fermentations.

Michael H. Peters is chair of the department. He received his Master's and PhD degrees from the Ohio State University in 1979 and 1981, respectively, and his BS from the University of Dayton in 1977. His research interests are in the areas of macromolecular dynamics, molecular transport phenomena, and molecular engineering. He is also a Faculty Associate with SCRI. His supercomputer computational research is being conducted in the general area of molecular and macromolecular dynamics. In the area of macromolecular dynamics, computer simulations, using Brownian dynamics methods, of coupled, internal translational and rotational motions of flexible macromolecules are being developed and tested. The significance of this work lies in the fact that internal macromolecular motions are often critical to the behavior and functionality of macromolecules. Some notable examples include biological macromolecules, such as DNA, t-RNA, and a variety of proteins and biopolymers, where internal flexibility or, more properly, the span of macromolecular

configurational space, is critical the degree of functionality of the macromolecule. Other supercomputer computational research is being conducted in the area of Natural Nonequilibrium Molecular Dynamics (NNMD). In this study, the goal is to include the boundary and initial conditions of the problem as they "naturally" occur in the real physical system. There are some extremely useful applications of this method despite the seemingly gargantuan system size. One application under development is the transport and deposition of aerosol particles in the human lung airways (e.g., bronchial and alveolar regions). Dr. Peters is also involved in research education in the field of molecular engineering and is currently working on a text entitled *An Introduction to Molecular Transport Phenomena*.

Samuel Riccardi, with a PhD from Ohio State University and over forty years of industrial experience at Olin Corporation, joined the department in 1988 as an adjunct professor. He devotes his time primarily to running the unit operations laboratory. He has also taught courses in design, thermodynamics, and industrial waste treatment. He has many interests in process and plant design, environmental control, and loss prevention in the process industries and has held positions in a wide range of areas including research and development, process engineering, pilot plant and manufacturing operations, plant and facility design, environmental control, and loss prevention.

After four years of academic experience at the University of Wisconsin-Madison, **John Telotte** was hired in 1985 as an assistant professor. He did his graduate work at the University of Florida under the direction of John O'Connell. His current research interests involve measurement and correlation of physical-property data and modeling of heterogeneous transport processes. The applications of these interests have been in the areas of biochemical processing, semiconductor processing, and indoor air quality. Ongoing research has been involved with both measurement and correlation of solubility data. A laboratory for complete thermodynamic characterization of dilute solutions has been set up and a solution theory has been developed that is generally applicable to solutions of a solute dissolved in a mixed solvent to analyze experimental data. Specific projects have examined amino acid solubility in mixed solvents and the effect of added salts on protein solubility and gas solubility in fermentation media. Initial work for semiconductor processing has focused on the measurement of diffusion coefficients of metalorganics in hydrogen and on viscosity mea-

surements of these mixtures. This will be extended to the development of correlations for transport properties. His work in indoor air quality is concerned with the development of models for radon transport through soil, modeling of the dynamics of radon distribution inside buildings, and the development of construction techniques to minimize hazards due to radon infiltration.

Most recently, **Jorge Viñals** has been appointed as an affiliate faculty with the rank of Graduate Research Professor. He is a research scientist at SCRI. He has a Masters and a PhD from the University of Barcelona, Spain, and has worked several years at Carnegie Mellon University under the direction of Professors Mullins and Sekerka. His research interests are centered around theoretical studies of non-equilibrium phenomena. Current areas of research include theoretical and numerical studies of kinetic processes during first-order phase transitions, morphological instabilities and growth during solidification, and pattern formation following fluid-flow instabilities. Dr. Viñals' efforts on phase transitions seek to understand and generalize scaling properties and to implement renormalization group techniques to situations far from the equilibrium. His research methods include the application of perturbation theory, Monte Carlo simulation, and numerical solutions to diffusion or Langevin-type equations. He is also interested in investigating the steady-state stability and transient evolutions of problems such as cellular morphologies, dendritic solidification, and viscous fingering instabilities.

The department has three additional affiliate professors. Within a framework emphasizing nontraditional areas in chemical engineering and multidisciplinary efforts, they work closely with other faculty members in directing graduate and undergraduate students and in developing new areas of research. They are **H. Garmestani** (PhD, Cornell University, 1989; Assistant Professor in the Department of Mechanical Engineering), **P. Gielisse** (Ph.D., Ohio State, 1967; Professor of Materials Science in the Department of Mechanical Engineering), and **H. Lim** (Ph.D., Rochester, 1986; Research Scientist for the SCRI).

FUTURE PERSPECTIVES

The faculty strongly believes that an interdisciplinary environment will provide the flexibility and the state-of-the-art knowledge required to develop successful chemical engineers for the future. The faculty also recognizes the crucial role played by research and graduate education in the overall performance of a successful program. Following studies to modernize

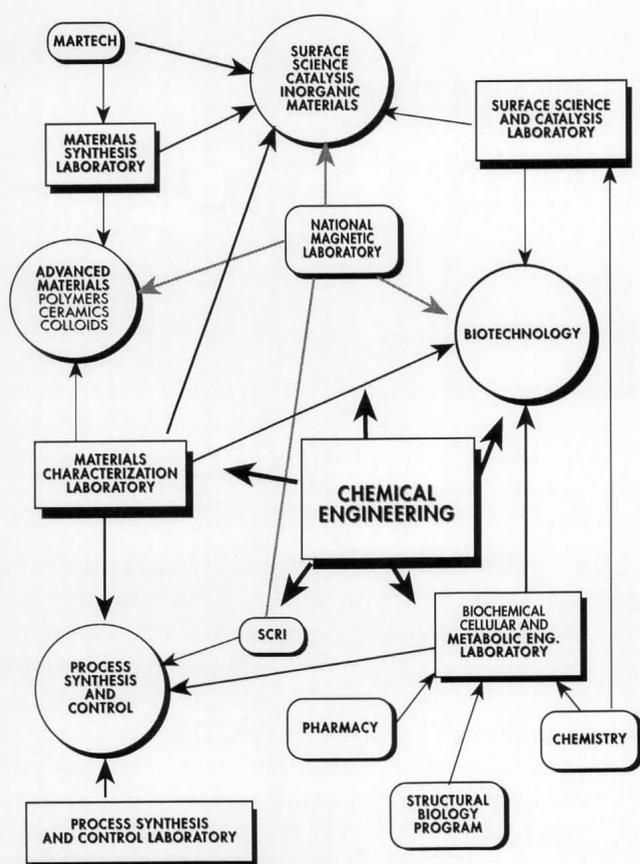


Figure 1. Present and future research focus for the ChE department at FAMU/FSU College of Engineering.

and to re-orient the chemical engineering programs across the country,^[1-3] the Department has formulated a strategic plan to focus on the development of research areas that will add to and supplement existing programs. These include developments in process control, surface science and catalysis, advanced materials, and biotechnology.

Figure 1 shows the four main areas of research mentioned above and the potential interactions that the different facilities and projects should display. One can see the important role played by the National High Magnetic Field Laboratory and the Supercomputer Computations Research Institute as well as the other first-class programs available at FSU and FAMU. It is the general philosophy of Dr. Jack Crow, director of the magnetic laboratory, that the university must integrate research at the lab with current programs in order to prevent the lab from becoming merely a user facility for outside researchers and to make it a valuable tool for building programs at the university. He has been successful at attracting internationally known experts in the areas of magnet design. J. Robert Schrieffer, 1972

Nobel prize winner in physics and former director of the Institute for Theoretical Physics at the University of California, Santa Barbara, joined the faculty in 1992. Also, Hans Jorg Schneider-Muntau, considered the best magnet designer in the world, joined the engineering faculty in 1992. Other well-known scientists have also joined the laboratory and become members of the faculty at FSU. They include John Miller (formerly at the Lawrence Livermore Laboratory), Dennis Markienicz (formerly at Intermagnetics General), and Steve Van Scriver (formerly at the Applied Superconductivity Center at Wisconsin). The lab will be located next to the engineering building, and both the chemical engineering and mechanical engineering departments have taken similar philosophies towards developing their programs to complement and fully utilize the lab.

The important role of SCRI is also crucial for the development of chemical engineering. FSU is one of the few universities in the United States to have both a state-of-the-art Cray Y-MP and a Connection Machine. The DOE-supported facility is currently used intensively by faculty in the chemical engineering department.

FAMU/FSU enjoys a unique multicultural atmosphere that is fostering development of a first-class chemical engineering department. The College of Engineering has appointed a new dean, Dr. C. J. Chen (ex-Iowa) who is actively working on important projects for the future of our college. In addition, the dynamic attitudes of the people involved in the various university research programs have created a critical mass of enthusiastic investigators who are driving the development of high-quality programs. With the current budgetary constraints facing most states (including Florida), few universities presently enjoy such a progressive atmosphere.

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A JUNGLE GUIDE THROUGH ACCREDITATION

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We, the authors of this paper, are both involved in engineering accreditation. Each of us has taught undergraduate chemical engineering for at least twenty-five years, and each of us continues to do so. Each of us has visited chemical engineering programs by request, to evaluate whether the programs meet nationally mandated accreditation criteria. One of us (JWP) is past president of the organization that develops and applies these criteria, and the other (ELC) headed the Educational Advisory Board of the American Institute of Chemical Engineers (AIChE).

Holding these positions has made us lightning rods for criticisms of the accreditation process. No one likes to be judged, and everyone gets angry about negative judgments. We have learned that any conversation beginning "What the *#! do you @*&!* think you're doing now?" usually introduces a reasoned comment on accreditation. Since this comment

often seems personal, and since any second comment often seems exactly the opposite of the first, we and our colleagues in accreditation often end up echoing Freud's comment on his patients: "My God, what do they want?"

While individual comments are usually emotional, we believe that many have merit. This merit, however, is often obscured by individuals who complain only every six years when their own program is up for review, or who use accreditation as a convenient weapon to fend off worthwhile curriculum reforms at home. Still, we believe that common concerns run through these complaints and that the concerns are often justified.

We will explore these concerns in this paper. Our experience suggests organizing them under three headings, each of which will be discussed in the following paragraphs:

- **What should the accreditation criteria be?**
- **How are the criteria applied?**
- **How can accreditation be improved?**

WHAT SHOULD THE ACCREDITATION CRITERIA BE?

To explore this issue, the AIChE Educational Advisory Board mailed 180 questionnaires to chemical engineering professors chosen from the listing in *Chemical Engineering Faculties*. We sent questionnaires to 60 department chairs and to a roughly equal number of tenured and untenured professors. This gave every department at least one chance to respond, and large departments had more chances than small ones. Such a selection is not scientific, and untenured faculty have the annoying tendency to get promoted and ruin the distribution! Still, we got 164 responses: 51 chairs, 87 tenured non-chairs, and 26 untenured non-chairs, for a total response of 91%. About ten more sent in unmarked questionnaires with notes such as "I hate questionnaires" or "My Dean doesn't let me say anything."

Edward L. Cussler received his BE (with honors) from Yale in 1961 and his MS and PhD from the University of Wisconsin, both in 1963. His research centers on new separation processes, especially those involving membranes. Some membranes currently under study are based on mobile carriers tethered within solid polymer membranes. He is Vice President of AIChE



John W. Prados received his BS at the University of Mississippi and his MS and PhD at the University of Tennessee. He has been at the University of Tennessee for 39 years, beginning as a graduate assistant in 1953, progressing through a number of professorial and administrative positions to his present position of Vice President Emeritus, University Professor, and Head of the Chemical Engineering Department.

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Overall Requirements • The results of this survey, summarized in Table 1, seem to reflect an overwhelming endorsement of the value of accreditation and of the existing chemical engineering curriculum. These endorsements were independent of position, *i.e.*, the responses of chairs, tenured faculty, and untenured faculty were the same. In particular, Table 1 shows that at least 86% of all respondents support the current requirements of one-half year of humanities, one year of mathematics and basic science, and one and one-half years of engineering.

Smaller majorities support the division of engineering into one year of engineering science and one-half year of engineering design. This split, which has proved to be almost impossible to judge fairly, is being reconsidered (as discussed in more detail below). Parenthetically, we note that these compelling endorsements of basic accreditation requirements are echoed by a parallel survey of engineering deans conducted by a joint task force representing ABET and the ASEE Engineering Deans' Council. On these issues, at least, chemical engineering faculty and deans agree.

Specific courses • The specific courses required for a chemical engineering degree are also endorsed by a large majority of faculty members. At least 89% support courses in basic mathematics, chemistry, and physics; 88% support a capstone course in

This wide agreement on the larger number of required courses means that most . . . faculty support a very rigid curriculum. . . . we are dismayed that so many of our colleagues subscribe to so many requirements.

design and one in separations; and still higher numbers endorse material on stoichiometry, transport processes, and reaction engineering. On these topics, all agree.

Not surprisingly, there is less agreement on what are often described as "emerging frontiers for chemical engineering." Slightly more than half of the respondents would require a materials course, and less than a quarter would require a course in biology. In more traditional areas, about three-quarters applaud engineering thermodynamics (we suspect that this lower percentage reflects uneasiness over possible repetition between the currently required thermodynamics courses). Sixty-three percent agree with the required one-half year of "advanced chemistry," a classification which can now include courses on microelectronics or advanced materials.

This wide agreement on the larger number of required courses means that most chemical engineering faculty support a very rigid curriculum. Quite frankly, we are dismayed that so many of our colleagues subscribe to so many requirements. To us, the best requirements would reflect *more flexibility*. Thus, we would not require specific courses in process control, materials, engineering thermodynamics, or biology for all departments, even while we might support some of these requirements for our own departments. In this sense, we urge all to think through the difference between nationally mandated criteria and those which are self-imposed at a single institution.

HOW ARE THESE CRITERIA APPLIED?

Armed with this strong consensus about what should be required, we now turn to the organizations responsible for engineering accreditation. For those who have not been involved in accreditation recently, we will briefly review the alphabet soup of acronyms involved. The key group is ABET (Accreditation Board for Engineering and Technology), a federation of some thirty-odd engineering societies. ABET is recognized by the USOE (United States Office of Education) and COPA (Council for Postsecondary Accreditation) as the only group authorized to accredit programs in engineering, engineering technology, and some engineering-related specialties within the United States and its territories. ABET gets the moral support of the engineering profession from its member societies,

TABLE 1
What Should the Accreditation Criteria Be?

(Source: Poll of 200 chemical engineering faculty members conducted in the fall of 1990 by the AIChE Educational Advisory Board.)

Curricular Requirement	% Favoring Requirement
Overall requirements should include at least:	
• 0.5 year of humanities and social science	86%
• 1.0 year of mathematics and basic science	92%
• 1.5 years of engineering	87%
• 1.0 year of engineering science	70%
• 0.5 year of engineering design	62%
Basic courses should include at least:	
• Mathematics through differential equations	96%
• General chemistry	93%
• General physics	89%
• One design course	88%
• Mass and energy balances	93%
• Fluid mechanics	94%
• Heat and mass transfer	94%
• Separation processes	88%
• Reaction engineering	93%
• One process control course	83%
• One engineering thermodynamics course	74%
• 0.5 year of advanced chemistry	63%
• One materials course	54%
• One biology course	22%

including AIChE. It also collects dues from them.

ABET accredits engineering programs through the EAC (Engineering Accreditation Commission), which conducts visits and votes accreditation actions for all engineering disciplines, as shown in Table 2. The AIChE interface with the EAC is the E and A Committee (Education and Accreditation Committee), a group of chemical engineers appointed by the AIChE Council. The EAC organizes accreditation visits, but the E and A Committee designates the chemical engineering visitors and exerts considerable influence on whether, and for how long, a chemical engineering program is accredited.

All of this can be confusing, especially since many call the E and A Committee the "ENA" Committee and don't understand that it's not the EAC. At one time, the E and A Committee did vote a separate accreditation on behalf of AIChE for each chemical engineering program, and ABET agreed to accept whichever action—EAC's or E and A's—was the more severe. For the past several years, chemical engineering programs have not been subjected to this kind of double jeopardy.

ABET evaluates programs against *general criteria* that apply to all fields of engineering and *program criteria* that apply only to a specific field. While both kinds of criteria must be approved by the ABET Board of Directors, the chemical engineering program criteria are recommended by the AIChE E and A Committee. This causes extra stress for chemical engineering programs in two ways:

1. Chemical engineering is the only major engineering discipline which depends heavily on chemistry. Thus chemical engineering curricula are always overcrowded by major infusions of chemistry in addition to the traditional "engineering core" based in physics. The E and A Committee has tried to ease the burden by counting other advanced sciences (*e.g.*, biology, materials science, solid-state physics) as part of the advanced chemistry requirement and by double-counting some advanced chemistry as a part of the engineering science requirement, but the extra stress remains.
2. A second source of irritation is the criticism by some ABET teams about faculty not being registered as Professional Engineers. Professional registration is much more important to disciplines such as civil and environmental engineering, whose graduates often work in private practice, than to others such as chemical and electrical engineering where most graduates work for large corporations. Edwin Layton, in his book *Revolt of the Engineers*, argues that some engineering societies are controlled by corporations who oppose professional registration as a form of unionism. In any case, registration is *not* required by the general criteria and only appears in a few program criteria, *e.g.*,

those for civil and environmental engineering. No chemical engineering program can be denied accreditation or have its accreditation term reduced just because its faculty are not registered. Still, since state registration board observers often accompany ABET teams, the issue is often raised—followed by the usual round of finger-pointing and ABET-bashing.

We provide a brief summary of chemical engineering accreditation requirements in Table 3. The Official Word is given in *Criteria for Accrediting Programs in Engineering in the United States*, published

TABLE 2
Accredited Engineering Programs as of November 1991
By Program Area
(299 Schools)

Source: 1991 Annual Report, ABET Engineering Accreditation Commission

Program Area	Bachelor's Level	Masters Level	Total
Aerospace*	57	4	61
Agricultural	46	0	46
Architectural	13	0	13
Bioengineering (incl. Biomedical)	20	0	20
Ceramic	12	0	12
Chemical	145	1	146
Civil, Construction*	212	1	213
Computer	69	2	71
Electrical, Electronic*	255	3	258
Engineering (undesignated)	31	0	31
Engineering Management	2	1	3
Engineering Mechanics	9	0	9
Engineering Physics, Science	28	0	28
Environmental*	11	8	19
Forest	2	0	2
Geological, Geophysical	18	0	18
Industrial*	93	1	94
Manufacturing*	10	3	13
Materials	30	0	30
Mechanical*	234	2	236
Metallurgical	30	0	30
Mineral	3	0	3
Mining	18	0	18
Naval Architecture and Marine	12	0	12
Nuclear	25	1	26
Ocean	6	2	8
Petroleum	21	0	21
Plastics	1	0	1
Surveying	6	0	6
Systems	11	1	12
Welding	1	0	1
Other	6	0	6
Less dual titles counted twice	(5)	0	(5)
Total Accredited Programs	1,432	30	1,462

* Five programs within these disciplines have dual titles (*e.g.*, Aerospace and Mechanical) and are counted twice.

each year by ABET, 345 East 47th Street, New York, NY 10017-2397. The requirements are always changing, so any department facing accreditation needs a current copy.

To seek chemical engineering accreditation, a university contacts ABET, requesting evaluation and completing a self-study questionnaire describing how its program satisfies accreditation criteria. ABET, through the EAC, organizes a visit by a team that includes a chemical engineering visitor designated by the E and A Committee. The visitor compares the criteria with the university's program as described by the self-study questionnaire; interviews the chemical engineering faculty and students; and examines course materials, including samples of student work. The visitor then writes a report which is reviewed by the team chairman, an EAC editor, the EAC chairman, and at least two members of the E and A Committee before it is sent back to the school for review and comment. The E and A Committee re-

views the visitor's report and the school's response and makes an accreditation recommendation; this recommendation is then presented to the EAC by one of the AIChE representatives. The EAC then takes the final accreditation action.

In spite of its Byzantine complexity, the system works. It presumes rational behavior by all concerned, and clearly, it relies especially heavily on the individual visitors. Still, the current accreditation system does have problems, and we discuss them in the next section of this paper.

HOW CAN ACCREDITATION BE IMPROVED?

We recognize that there are many complaints about accreditation, and that most people complain when they are being critically judged. Because the complaints are often vehement, we are reassured by the fact that such a wide percentage of faculty support both the general concept of accreditation and its specific requirements, as detailed above. We believe that the system for carrying out accreditation is effective, although ponderous.

The system seems to work best for chemical engineering—over the last five years, two-thirds of the chemical engineering programs visited received accreditation for the maximum term of six years, although some were required to submit written reports after three years to describe correction of problems observed at the time of the original visit. *This percentage of programs receiving six-year accreditation is higher than that for any other major engineering discipline.*

At the same time, we know that there are problems with the current system. We see four of these as

- the design requirement
- the self-study questionnaire preparation
- the visitors who evaluate programs
- the need for educational innovation

Each problem merits consideration and is discussed more fully in the following paragraphs.

The Design Requirement • Twenty years ago, the accreditation criteria did not include any quantitative statement on engineering design. Beginning in 1972, accredited programs were required to include at least one-half year of "design, synthesis, and systems," in addition to the existing requirement of one year of engineering science, and two years later the present requirement of one-half year of engineering

TABLE 3
Brief Summary of
Chemical Engineering Accreditation Requirements

I. Faculty

- A. Absolute minimum is three full-time equivalents devoted to the undergraduate program; more are required for graduate program, research, courses offered to non-chemical engineers, etc.
- B. Appropriate professional education, experience, and growth

II. Curriculum

- A. Quantitative:
 - 1.0 year of mathematics (beyond trigonometry and through differential equations) and basic science (including chemistry and physics)
 - 1.0 year of engineering science
 - 0.5 year of engineering design
 - 0.5 year of humanities and social science
 - 0.5 year of advanced chemistry (chemical engineering only)
- B. Qualitative:
 - Appropriate laboratory experience
 - Appropriate computer experience
 - Knowledge of probability and statistics
 - Competency in written and oral communication
 - Understanding of ethical, social, economic, and safety issues

III. Students

- A. Appropriate preparation for engineering study
- B. Maintain information on performance of graduates

IV. Administration

- A. Adequate support for and commitment to engineering program

V. Facilities

- A. Adequate classrooms, offices, laboratories, library, computers
- B. Functioning plan for laboratory maintenance and modernization

VI. Institutional Commitment

- A. Adequate level of financial support for program

design went into effect. These changes reflected a real concern that engineering faculty were becoming obsessed with mathematical analysis and were not giving students experience with open-ended problems where economic and social judgments are important. We are sympathetic to this concern.

However, a reliable evaluation of the quantitative split between engineering science and engineering design has proved to be impossible in almost every engineering discipline. One visitor commented that design is like pornography—he couldn't define either, but he knew it when he saw it!

Such a definition is not very helpful in maintaining consistency with different visitors or in planning curricular changes. Visitors have had great difficulty in judging whether a unit operations course contains 20%, 30%, or 50% design. More than one chemical engineering department has been told that its curriculum had barely enough design, but was acceptable—then six years later, a different visitor judged the same curriculum deficient in design by 5-6 semester credits. The EAC and the E and A Committee work very hard to try to make consistent judgments in a given year, but have trouble remembering what happened six years ago. It has been a mess.

As a result, the EAC has proposed combining the present engineering science and engineering design requirements into 1.5 years of "engineering topics." These must include a "meaningful, major design experience" that is developed throughout the curriculum and culminates in one or more capstone courses that integrates earlier technical work with economic, safety, and environmental constraints. For chemical engineering, this means a strong senior process design experience and the generous use of open-ended problems and projects in courses such as material and energy balances, unit operations, and chemical reaction engineering. The department must show how it meets the design requirement in its self-study questionnaire and its course materials exhibits. The key question for the visitor will be how well the curriculum develops student abilities to attack problems with more than one right answer, to communicate, to work in teams, and to understand the non-technical contributions to engineering decisions.

We are pleased with this overdue change. It will not in any sense reduce the emphasis on design, but it *will* focus attention on the quality and rational development of the student's design experience and move us away from the unproductive bean-counting of the last eighteen years. However, the change is not yet in place. It was approved on first reading by the ABET Board of Directors in October of 1990, but will

not go into effect for at least two years (to allow public comment), and so a society that wants to insist on a quantitative design requirement can propose one for its program criteria. The earliest date for final approval would be October of 1992, with the change effective for visits in the fall of 1993.

Preparation of the Self-Study Questionnaire

- The accreditation procedure requires preparing a self-study questionnaire which details factors such as the economic health of the institution, the professional activities of faculty members, and the syllabi of all required courses. The completed questionnaire, in two volumes, can run to hundreds of pages. Preparation is a chore that can take as much as a year out of some unfortunate person's life. While the questionnaire contains much useful information, many complain that it is too long, too elaborate, too detailed, and too much work.

We agree. But we are unsure of how to improve the situation. Short biographies of all faculty provide important details (such as industrial and consulting experience) which go beyond existing sources like the *ACS Directory of Graduate Research*. Course descriptions and syllabi are also necessary, especially since catalog descriptions are cryptic, dated, and often unreliable. We agree that the best way to evaluate a course is to look at excellent notes, exams, homework, and sample student papers assembled by the professor in charge of the course. Unfortunately, we find that an embarrassing number of professors do not keep excellent notes, let alone exams.

Moreover, we believe that preparing the self-study questionnaire is an effective challenge for engineering deans. They may be paragons of fairness and virtue, but they are subject to major pressures that involve hard choices. These choices are usually financial and, in our opinion, are often resolved to the detriment of the chemical engineering program—this may be because chemical engineering's chemical basis is expensive and not completely understood. Preparing the questionnaire forces every dean to justify decisions to relatively impartial outside observers untarred by local politics. Still, we recognize that preparing the questionnaire is onerous work, and we welcome suggestions for making it easier.

- ***The Accreditation Visitors*** • The third problem with the accreditation process is the visitors themselves, who do the on-site evaluation of how well an engineering program satisfies the ABET criteria. Such visits are not fun. They require deciphering almost inevitably tangled, incomplete questionnaires and incomprehensible student transcripts. Trying to determine course content, credit-hour distributions,

and what students are *really* required to do can be difficult. Moreover, the accreditation team is under such intense time pressure that the visitor cannot even see professional colleagues and friends at the school being visited.

Most visitors do a good job. The E and A Committee works hard to insure that the visitors (known as "program evaluators" in the trade) are trained for their task; each must attend a three-hour accreditation workshop and then go on one accreditation visit as an observer before serving as an evaluator. However, even with this help a few of them still apply too rigorously the standards they think they remember from their own education, perhaps thirty years earlier . . . or disregard the criteria and inject their own educational theories into the evaluation. The E and A Committee must learn of these biases quickly and correct them in any summary report. Repeat offenders are not assigned to new visits. In addition, any school can object beforehand to an individual visitor who may have a conflict of interest or is thought to be biased. However, one school objected to 80 of 83 potential visitors, an action interpreted as an effort to predetermine the outcome of the visit.

We are indebted to those currently serving as visitors, and we are eager to encourage more who are interested. We recognize that we can offer no rewards but the feeling of service and the chance to work with other professionals in doing a job well. We admit that serving as a visitor is an invitation to criticism; every visitor who finds something lacking in a program runs the risk of vilification. At the same time, we always need good, new visitors—especially those underrepresented in our current pool. These underrepresented segments include women, minorities, and those with significant industrial experience (most of all, those with experience both in industry *and* in teaching).

If you—you, there—were critical of your last accreditation visitor, and yet (like most of us) believe that accreditation has value, why not volunteer?

Educational Innovation • Finally, we want to stress that the accreditation criteria do allow exemptions for educational innovation. We are dismayed that few departments, if any, seek accreditation on this basis. We can imagine many good reasons for such failure. One reason may be a university-wide core curriculum that restricts student choice; such curricula can cripple chemical engineering programs. Another, probably more significant, reason is the fear that deviations from a "standard" chemical engineering curriculum taught in a "standard" manner will jeopardize a program's accreditation.

Winter 1993

The chemical engineering program criteria require coverage of certain subjects, but don't specify how much time must be devoted to each of them. If you feel that your curriculum could be improved by reducing duplicate coverage in thermodynamics and increasing student electives, why not give it a try? Why not consider replacing traditional mathematics courses with "just-in-time" modules? How about the possibility of eliminating certain required courses altogether and replacing them with student projects? If you are concerned with how these innovations affect your accreditation, discuss your goals with the E and A Committee as part of your planning.

EPILOGUE

In the final analysis, accreditation is a creature of the engineering profession, heavily influenced by engineering educators. Faculty members and deans make up the majority of the E and A Committee, the EAC, and the ABET Board of Directors. If accreditation is a problem, you and we are a big part of that problem—and you and we *must* be a big part of its solution. □

ChE conferences

International Conference on Natural Gas Hydrates

June 20-24, 1993

Lake Mohonk Mountain House; New Paltz, New York

Meeting purpose is to determine the state-of-the-art of natural gas hydrate knowledge and to determine the areas in which future work will be needed. A broad field of noted researchers will present the latest findings and will be available to exchange views aimed at bringing the current science and engineering of hydrate formation, control, and utilization into focus. Conference Steering Committee: E. Dendy Sloan (Colorado School of Mines) and John Happel (Columbia University). For further information, contact Conference Department, New York Academy of Sciences, 2 East 63rd Street, New York, NY 10021 (212-838-0230) □

Reaction Engineering and Applied Catalysis

May 12-14, 1993

The University of Michigan; Ann Arbor, Michigan

Fee: \$765

Chemical reactions occur in a variety of different systems and are essential in numerous technological areas including the automotive industry, the chemical and petroleum industries, and environmental engineering. The goal of this course is to provide a background in the practical aspects of kinetics, catalysis, and reaction engineering. The fundamentals of kinetics, catalysis, and transport will be applied in the analysis and design of reaction systems. For complete information or to register, contact Engineering Conferences, 300 Chrysler Center, North Campus, The University of Michigan, Ann Arbor, MI 48109-2092 (313-764-8490) □

LIQUID-PHASE AXIAL DISPERSION IN A PACKED GAS ABSORPTION COLUMN

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The cost of electronic instrumentation has come down recently as a result of newer technologies and lower computer prices. We have taken advantage of this trend to create new and dynamic experiments using existing steady-state experiment apparatus. Our purpose was to enhance the learning process by removing some of the data-collection tedium and thereby leaving more time for experimental design and analysis.

One of our upgraded experiments is a packed-column apparatus used for the absorption of CO₂ into water. The column was instrumented with conductivity probes to indirectly measure inlet and exit liquid-phase concentrations. Large amounts of real-time data are readily acquired with the aid of a computer. For example, accurate unsteady-state and steady-state operations are easily observed. It is common to assume plug-flow conditions when analyzing mass transfer in a packed column. This paper presents an experiment and analysis to examine the validity of this assumption in the liquid phase.

In the first part of the experiment, the residence time distribution (RTD) of the liquid phase is determined by measuring the exit response to an impulse concentration perturbation on the liquid feed. The second half of the experiment consists of determining the overall liquid-phase mass transfer coefficient from gas-absorption measurements in the packed column. The results from the RTD experiments are used in a dispersion model to account for deviations from plug flow (e.g., back mixing in the liquid phase). Dispersion effects on mass transfer are evaluated by comparing mass transfer coefficients calculated assuming plug flow with mass transfer coefficients calculated from non-ideal flow conditions. This new

approach adds a degree of difficulty to the experiment by removing the plug-flow constraint and provides a setting wherein students can make critical judgements on a well-known solution.

THEORY

A model of dispersion in the liquid phase is developed for flow without interphase mass transfer to obtain a dispersion coefficient. The results are used in a second model which accounts for dispersion with interphase mass transfer in a packed column. A model for the limiting case of plug flow is also presented.

Dispersion Model

Levenspiel^[1] presents the dispersion model for deviations from plug flow in the axial direction as

$$\frac{\partial C}{\partial t} = E \frac{\partial^2 C}{\partial z^2} - u \frac{\partial C}{\partial z} \quad (1)$$

Richard Davis received his BS degree in chemical engineering from Brigham Young University and his PhD from the University of California, Santa Barbara. He is a member of the chemical engineering faculty at the University of Minnesota, Duluth. His research and teaching interests are in the areas of separation processes and environmental remediation.



Joe Doyle holds a BS in chemistry from UCSB and is a Development Engineer in its Chemical and Nuclear Engineering Department. His interests include analytical instrumentation, data-acquisition systems, and exploration of the world's largest aqueous sodium chloride reactor.



Orville Sandall is a professor in the Chemical and Nuclear Engineering Department at UCSB. He is a graduate of the University of Alberta (BSc, MSc) and the University of California, Berkeley (PhD). His teaching and research interests are in the areas of mass transfer and separation processes.

where C = concentration
 t = time
 z = axial coordinate
 u = superficial liquid velocity
 E = dispersion coefficient which characterizes convective back-mixing as well as diffusion

Usually, the dispersion coefficient is much larger than the diffusion coefficient. Eq. (1) can be made dimensionless as follows:

$$\frac{\partial C}{\partial \theta} = \left(\frac{E}{uh}\right) \frac{\partial^2 C}{\partial z^{*2}} - \frac{\partial C}{\partial z^*} \quad (2)$$

where the quantity

E/uh = the dispersion number (=1/Pe)

h = the length of the column.

The dimensionless variables are

$$\theta = \frac{t}{\tau} \quad (3)$$

where τ is the mean residence time

$$\tau = \frac{h}{u} \quad (4)$$

and

$$z^* = \frac{z}{h} \quad (5)$$

The concentration is normalized such that

$$C = \frac{C}{Q}$$

where

$$Q = \int_0^\infty C \, dt \quad (6)$$

Thus we have

$$\int_0^\infty C \, dt = 1 \quad (7)$$

Eq. (2) is examined for two regimes: small and large extents of dispersion.

For an impulse perturbation of tracer on a fluid with little dispersion, the shape of the tracer curve does not change significantly from the point of injection to the measurement point. The C curve at the measurement point is a Gaussian distribution.

$$\tau C = \frac{1}{2\sqrt{\pi\left(\frac{E}{uh}\right)}} \exp\left[-\frac{(1-\theta)^2}{4\left(\frac{E}{uh}\right)}\right] \quad (8)$$

The dispersion coefficient can be obtained by two relatively simple methods. First, at the mean residence time, $\theta = 1$ and the C curve reaches a maximum. Eq. (8) may be solved for the dispersion number in terms of C_{\max}

$$\frac{E}{uh} = \frac{1}{4\pi} \left(\frac{1}{\tau C_{\max}}\right)^2 \quad (9)$$

In a second method, the variance of the C curve can be expressed in terms of the dispersion number

$$\frac{\sigma^2}{\tau^2} = 2\left(\frac{E}{uh}\right) \quad (10)$$

The variance is defined as

$$\sigma^2 = \int_0^\infty t^2 C \, dt - \tau^2 \quad (11)$$

The solution for the dispersion number is found by rearranging Eq. (10) to give

$$\frac{E}{uh} = \frac{\sigma^2}{2\tau^2} \quad (12)$$

For small extents of dispersion, the experimental procedure and analysis are straightforward because the shape of the C curve is insensitive to the boundary conditions imposed on the packed column.

A characteristic of large extents of dispersion is an unsymmetrical response to an impulse perturbation about the mean residence time. The C curve typically has an extended tail. In this case, the boundary conditions become important. The current experimental setup in our laboratory is best described by closed boundary conditions (*i.e.*, the flow pattern changes abruptly at the boundaries). In this case, there is no analytical solution for the C curve. The variance of the C curve is given as

$$\frac{\sigma^2}{\tau^2} = 2\left(\frac{E}{uh}\right) - 2\left(\frac{E}{uh}\right)^2 \left\{1 - \exp\left[-\left(\frac{uh}{E}\right)\right]\right\} \quad (13)$$

The dispersion number may be found by determining the variance as defined by Eq. (11) and then solving the non-linear Eq. (13) for E/uh by Newton's iterations. Good initial guesses for E/uh can be obtained by using Eqs. (9) and (12) to solve for E/uh . Levenspiel^[2] offers the following estimates for the extent of dispersion:

small: $E/uh < 0.01$ large: $E/uh > 0.01$

Tanks-In-Series

Levenspiel^[1] also presents the tanks-in-series (TIS) model to account for deviations from plug flow conditions. In this model, the liquid flows through a series of n completely mixed stirred tanks. The C curve for this model is

$$\tau C = \frac{(\theta n)^n}{\theta(n-1)!} \exp(-\theta n) \quad (14)$$

The number of tanks can be determined from the value for C_{\max}

$$\tau C_{\max} = \frac{n(n-1)^{n-1}}{(n-1)!} \exp(1-n) \cong \frac{n}{\sqrt{2\pi(n-1)}} \quad \text{for } n > 5 \quad (15)$$

A simpler technique uses the value of θ_{\max}

$$n = \frac{1}{1 - \theta_{\max}} \quad (16)$$

The dispersion number is related to the number of tanks as

$$\frac{E}{uh} = \frac{1}{2n} \quad (17)$$

Differential Model with Dispersion

King^[3] discusses a differential model which includes dispersion effects for a stripping column in counter-current flow. A simplified version of this model for absorption is developed here. The current experimental apparatus limits the study of dispersion effects to the liquid phase. Thus, the experiments are designed so that dispersion in the gas phase is unimportant. This is accomplished by using 100% CO₂ in the gas phase for absorption experiments. Thus, the mole fraction of CO₂ in the gas phases remains constant for our experimental design. An idealized picture of the flow conditions in a counter-current gas-liquid absorption column is shown in Figure 1.

A shell balance around a differential element of the column gives the transport equation for the liquid phase as

$$LC_L \frac{dx}{dz} + EAC_L \frac{d^2x}{dz^2} + K_L aA (x_e - x) = 0 \quad (18)$$

where L = volumetric liquid flow rate

K_L = overall liquid phase mass transfer coefficient

a = effective interfacial area per unit volume

A = cross-sectional area of the column

C_L = concentration of the liquid phase

x = mole fraction of the solute in the liquid stream at position z

For the small mass transfer rates considered here, it is assumed that G , L , C_L , and K_L are constant. The subscript e indicates equilibrium conditions. If the equilibrium relationship between the phases is linear (which is the case for our system of dilute CO₂ in water) then x_e can be replaced by the equilibrium relationship

$$y = mx_e \quad (19)$$

The boundary conditions are discussed in Lo, *et al.*^[4] At the liquid entrance, the net axial solute transport away from the upper boundary is equated with the solute feed into the boundary

$$LC_L x_f - EAC_L \frac{dx}{dz} = LC_L x \quad (20)$$

where the subscript f indicates feed conditions. Eq. (20) can be written as

$$(x_f - x) = \frac{EA}{L} \frac{dx}{dz} \quad \text{at } z = h \quad (21)$$

The same argument as above leads to a similar condition at the liquid exit boundary

$$(x - x_0) = \frac{-EA}{L} \frac{dx}{dz} \quad \text{at } z = 0 \quad (22)$$

The left- and right-hand sides of Eq. (22) are of opposite sign. Thus, Eq. (22) is only valid for the case where $x = x_0$. This result is summarized as follows

$$\frac{dx}{dz} = 0 \quad \text{at } z = 0 \quad (23)$$

The balance is made dimensionless as follows (noting that, for the case considered here, x_e is constant since pure CO₂ is absorbed)

$$\frac{dX}{dw} + \frac{1}{Pe} \frac{d^2X}{dw^2} - NX = 0 \quad (24)$$

where

$$X = x_e - x \quad (25)$$

$$w = \frac{z}{h} \quad (26)$$

$$Pe = \frac{Lh}{EA} = \frac{uh}{E} \quad (27)$$

$$N = \frac{K_L ahA}{LC_L} \quad (28)$$

The dimensionless boundary conditions are

$$\frac{dX}{dw} = 0 \quad \text{at } w = 0 \quad (29)$$

$$Pe(X_f - X) = \frac{dX}{dw} \quad \text{at } w = 1 \quad (30)$$

The Peclet number, defined in Eq. (27), is the inverse of the dispersion number in Eq. (2). Note also that, as $Pe \rightarrow \infty$, the transport equation reduces to the plug-flow equation.

Equation (24) is linear and homogeneous and can be conveniently solved by the method of undetermined coefficients. From inspection of Eq. (24), the

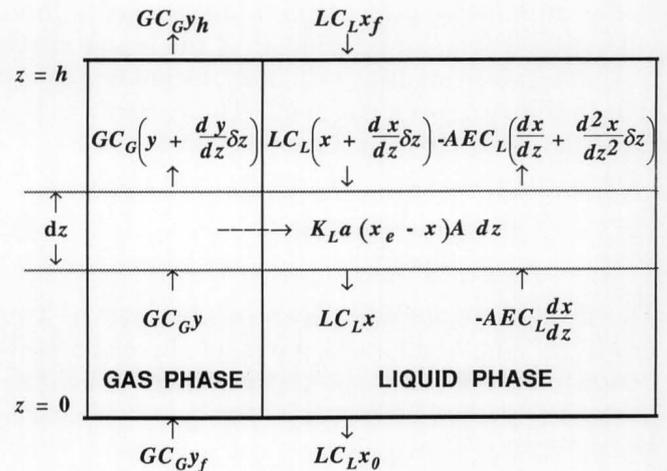


Figure 1. Idealization of gas-liquid contacting in a packed column.

solution for X must be of the form

$$X = c_1 e^{(d_1 w)} + c_2 e^{(d_2 w)} \quad (31)$$

where d_i are the roots of the characteristic equation

$$d_i = \frac{-Pe \pm \sqrt{Pe^2 + 4 Pe N}}{2} \quad (32)$$

The integration constants, c_i , are determined from application of the boundary conditions. The result is

$$c_1 = \frac{d_2 Pe X_f}{d_2 (Pe + d_1) \exp(d_1) - d_1 (Pe + d_2) \exp(d_2)} \quad (33)$$

$$c_2 = \frac{d_1 Pe X_f}{d_1 (Pe + d_2) \exp(d_2) - d_2 (Pe + d_1) \exp(d_1)} \quad (34)$$

The experimental results are applied to this solution to predict the overall mass transfer coefficient combined with the effective interfacial area per unit volume, $K_L a$. The effects of axial dispersion on the overall mass transfer coefficient can be observed by comparison with predictions from the solution to the model for plug flow.

Plug Flow Model

In the case of plug flow, the second order term in Eq. (24) is dropped. The resulting transport equation can be integrated directly for dilute systems where the driving force $(x_e - x)$ is a linear function in x . The solution is

$$N = \frac{K_L a h A}{LC_L} = \frac{(x_0 - x_f)}{(x_e - x)_{lm}} \quad (35)$$

where the log-mean driving force is defined as

$$(x_e - x)_{lm} = \frac{(x_e - x)_0 - (x_e - x)_f}{\ln \left[\frac{(x_e - x)_0}{(x_e - x)_f} \right]} \quad (36)$$

The subscripts 0 and f indicate the conditions at $z = 0$ and h , respectively. The details for the derivation of Eq. (35) are found in Bennett and Myers.^[5] The solution to the plug-flow model can also be obtained by solving the general model for large values of Pe .

APPARATUS AND PROCEDURE

A diagram of the apparatus is shown in Figure 2. The apparatus consists of two identical 4-inch inside diameter glass columns packed with 4 feet of 1/2-inch ceramic Intalox saddles. One column is used for gas-absorption experiments and the other for stripping operations. To conserve water, the columns are arranged so that water can circulate through both columns simultaneously in the case of absorption experiments. In the case of tracer experiments, water is pumped from a 30-gallon plastic storage tank to the top of the absorption column. The liquid feed is distributed evenly over the top of the packing and allowed to flow through the packing. The exit stream is collected in a separate 30-gallon holding tank. The liquid flow rate is measured with a rotameter and an electronic flow meter. The flow rate is controlled by a valve that restricts liquid recirculation to the pump. The lower limit on the liquid flow rate is approximately two gallons per minute. Below this limit we found that the packing did not completely wet. The upper limit is set at approximately four gallons per minute to avoid flooding. Custom conductivity probes by Microelectrodes[®] are situated in the liquid feed and exit streams just above and below the packing to determine the inlet and exit liquid concentrations. The conductivity probes are situated so that a mixing-cup measurement is obtained at the exit stream of the liquid phase. CO_2 and N_2 gas are passed to the bottom of the packing through rotameters and electronic mass flow meters. The gas flow rates are controlled by needle valves. The temperatures of the gas/liquid feed and exit streams are measured with thermocouples. An IBM personal computer is used to monitor the gas/liquid flow rates and the liquid conductivities. The software Labtech Notebook[®] is used to collect and display the signals from the column on the computer. The data are imported directly to the spreadsheet program Lotus 123[®] for manipulation and analysis.

The procedure for the gas absorption experiment consists of setting the gas and liquid flow rates and monitoring the liquid-phase conductivities until a

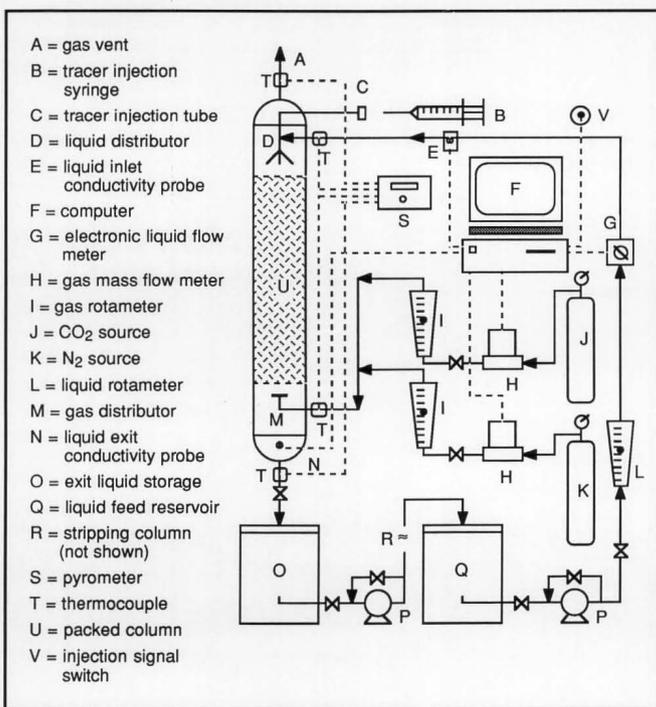


Figure 2. Packed-column apparatus used in tracer and absorption experiments.

steady state is reached. The conductivity probes are calibrated against aqueous CO_2 solutions with known concentrations by titration. Each student group carries out its own calibration. The CO_2 is fixed in solution by adding excess NaOH , then precipitated with BaCl_2 . The excess NaOH is titrated with HCl . Pure CO_2 gas was used in the absorption column to avoid gas-phase dispersion effects. The stripping column uses N_2 gas.

In the case of tracer experiments, the conductivity of the liquid is monitored to achieve a base line. Approximately 1 ml of 5 M HCl is injected through a 1/16-inch ID Teflon tube into the liquid feed just before the liquid distributor at the top of the column. The volume of the injection tube is approximately 1 ml. A rubber septum caps the end of the injection tube in order to prevent tracer fluid from being forced back out of the tube, and an electric switch is provided to record the beginning and duration of the tracer injection period. It can be assumed that the initial perturbation approaches an impulse or delta function if the time period of the tracer injection is small relative to the time span for the signal at the bottom of the column. With the arrangement described here, we found that it required approximately 0.25 seconds to inject the tracer. This may be compared to mean residence times greater than 20 seconds. The conductivity data of the liquid exit stream are collected until the value of response returns to the base line. The conductivity of HCl was found to be a linear function of concentration over the range of conditions for this experiment. Therefore, it is unnecessary to calibrate the conductivity probes for HCl because the response to the tracer is normalized for the total amount of tracer injected.

ANALYSIS OF RESULTS

The analysis has two parts: calculation of the dispersion coefficient, and calculation of the overall liquid-phase mass transfer coefficient combined with the effective interfacial area per unit volume. A computer spreadsheet is used to convert the tracer-experiment data to a usable form.

The RTDs from tracer experiments are used with the dispersion model to obtain a dispersion number. It must be assumed that the tracer injection is an ideal impulse perturbation because the variance at the top of the column cannot be obtained experimentally from our arrangement. For either small or large extents of dispersion, it is necessary to calculate the variance of the RTD for the tracer at the liquid exit. Initially, the baseline concentration signal is subtracted from all the concentration data. The mean residence time and variance are obtained from the

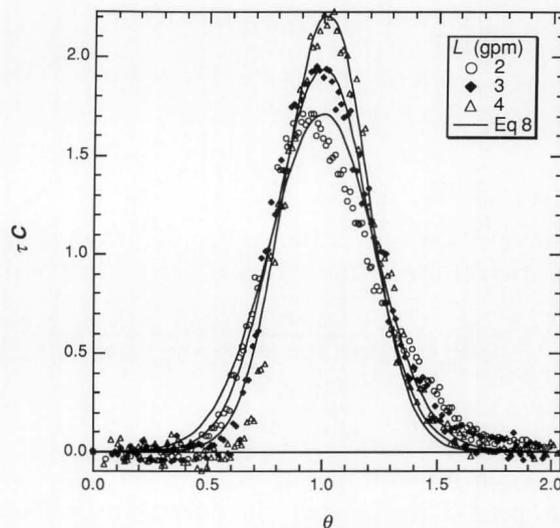


Figure 3. C curves from tracer experiments compared with the small extent of dispersion model

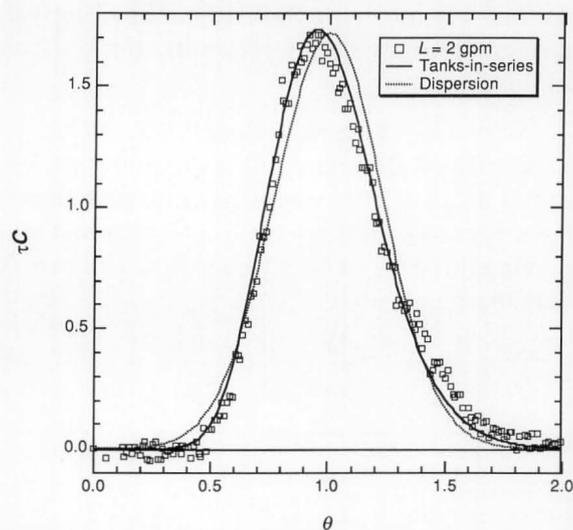


Figure 4. Comparison of tanks-in-series and the small extent of dispersion models for intermediate-to-large extent of dispersion.

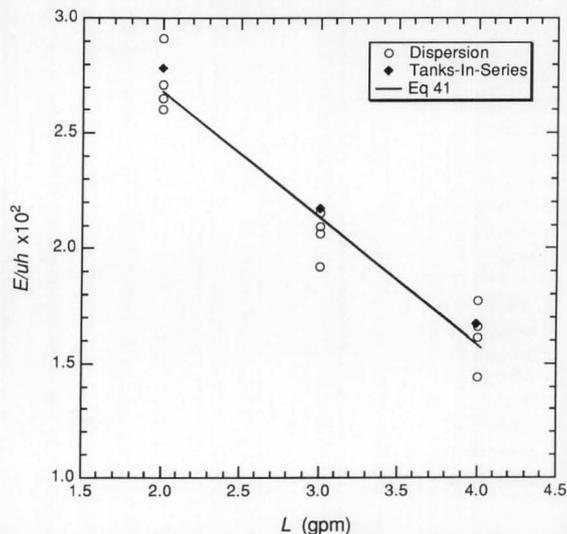


Figure 5 Experimental results for the dispersion number as a function of L .

discrete concentration vs time data according to the following approximations^[1]

$$Q \cong \sum_{i=1}^N C_i \Delta t \quad (37)$$

$$C_i \cong \frac{C_i}{Q} \quad (38)$$

$$\tau \cong \sum_{i=1}^N t_i C_i \Delta t \quad (39)$$

$$\sigma^2 \cong \sum_{i=1}^N t_i^2 C_i \Delta t - \tau^2 \quad (40)$$

where Δt is the time interval between sampling, and N is the number of data pairs. Experimental C curves are plotted in Figure 3 for three liquid flow rates. Care must be taken when applying Eqs. (37) to (40) to the experimental data. The final results may depend on the choice of the last data point due to the scatter in the measurements around the base line. When this is difficult, Levenspiel^[2] suggests drawing a curve through the data by hand and picking points at uniform intervals from the curve.

The dispersion numbers were determined from Eqs. (9), (12), or (13), depending on the extent of

dispersion. The criteria for determining the extent of dispersion is based on the shape of the C curve. As seen in Figure 3, there is little dispersion for liquid flow rates of 3 and 4 gallons per minute. At 2 gallons per minute, the shape of the C curve begins to deviate from the symmetric Gaussian distribution of Eq. (8), indicating a larger extent of dispersion. The TIS model was found to fit the data better than the small dispersion model at this low flow rate. Both models are compared in Figure 4. A numerical solution of Eq. (2) is necessary to obtain the dispersion model C curve for large extents of dispersion. This is beyond the scope of the present experiment.

In order to demonstrate the procedure, four tracer experiments were performed at each of the three flow rates above. The experimental results for the dispersion number from the dispersion and TIS models are plotted in Figure 5. They indicate small-to-intermediate amounts of dispersion in the packed column. For this limited range of operating conditions, the results for the dispersion number from the dispersion model can be correlated by a least-squares method to Eq. (41)

$$\frac{E}{uh} = 0.038 - 0.0055 L (\text{gpm}) \quad (41)$$

A similar correlation was found from the TIS results for the dispersion number. The dispersion number is a decreasing function of liquid flow rate. This indicates that plug flow conditions are approached as the liquid flow rate increases. This may be due to a decrease of liquid stagnation in the packing at higher flow rates.^[6]

Dispersion numbers from Eq. (41) are used in the differential model to predict $K_L a$, assuming the tracer measurements are valid under mass-transfer conditions. This is probably a good assumption in this case since a relatively small quantity of CO_2 is absorbed. The non-linear transport equation for the liquid phase, Eq. (31), is readily solved for $K_L a$ by application of Newton's method with a computer. The solution method requires guessing values for $K_L a$ until the calculated exit conditions match the experimental results for the liquid-phase exit concentration. The experimental data and results are listed in Table 1 and the calculations for $K_L a$ are compared with the plug-flow case in Figure 6. The largest deviation from the plug-flow model was found to be approximately 4%. It is important to note that dispersion in the liquid phase has a negative effect on gas absorption. This is demonstrated here by the difference in magnitude of $K_L a$ for each case. $K_L a$ for the dispersion model must be larger to achieve the same separation as the plug-flow model.

L ($\frac{\text{gal}}{\text{min}}$)	x_i	x_o	E/uh	$K_L a$ ($\frac{\text{lbmol}}{\text{ft}^3 \cdot \text{hr}}$)		% Deviation
				Dispersion	Plug Flow	
2.0	0.00012	0.00049	0.027	243	234	3.7
3.0	0.00016	0.00049	0.022	340	330	2.9
4.0	0.00017	0.00048	0.016	414	405	2.2

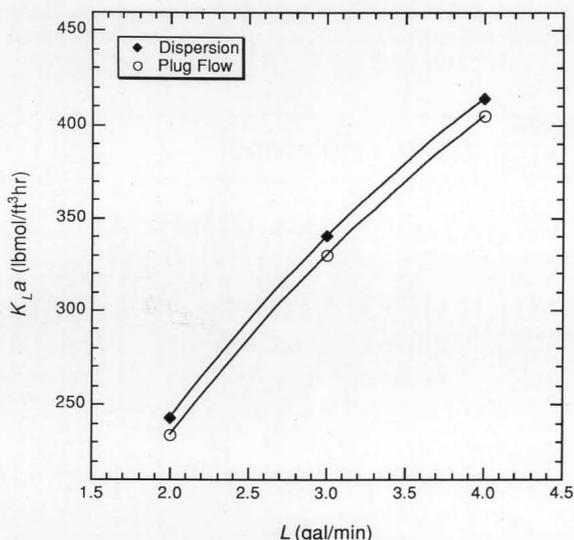


Figure 6. Comparison of $K_L a$ from plug flow and dispersion models.

DISCUSSION

The results from the analysis reveal that, for our absorption column, dispersion effects are small over the range of operating conditions reported. Thus, the plug-flow assumption is valid in this case, and the analysis of the mass transfer coefficient is simple. Often, simplifying assumptions are presented without justification. This new experiment provides students with the opportunity to verify the assumptions that are used to derive the well-known result for the mass transfer coefficient in a packed column. In this paper we chose to present the differential model as the one most closely representing the physical characteristics of the flow pattern through the packing. The students are not limited, however, to this model to explain deviations from plug flow. Levenspiel,^[1] Lo, *et al.*,^[4] and King^[3] describe several models used for this purpose. For small-to-intermediate extents of dispersion, a tanks-in-series model with back flow is commonly employed. Other models use recirculation, back mixing, dead volumes, and combinations of these in conjunction with the tanks-in-series model. These models are much more cumbersome, and we found the dispersion and the tanks-in-series models adequate for our purposes.

The apparatus described here was designed at UCSB and was constructed by an off-campus contractor at a cost of \$12,000. The electronic instrumentation was an additional \$6,000. The apparatus is used in each of our required two-quarter sequence courses in Chemical Engineering Laboratory. In the first-quarter course, steady-state data are taken to determine mass transfer coefficients, and in the second quarter the axial dispersion measurements described here are carried out.

ACKNOWLEDGEMENT

The authors benefitted from many enlightening discussions with Professor R.G. Rinker regarding the modeling of dispersion. This work was sponsored by a Teaching Assistant Instructional Grant funded by the UCSB Instructional Improvement Program.

NOMENCLATURE

- a = interfacial area per unit volume, ft⁻¹
- A = cross-sectional area of empty column, ft²
- c_i = integration constants, Eqs. (33) and (34)
- C = concentration, lbmol-ft⁻³
- C = normalized concentration, s⁻¹
- d_i = roots to characteristic equation, Eq. (32)
- E = dispersion coefficient, ft²·s⁻¹
- G = volumetric gas flow rate, ft³·hr⁻¹
- h = column height, ft
- K_L = liquid phase overall mass transfer coefficient, lbmol·ft²·s⁻¹
- L = volumetric liquid flow rate, ft³·hr⁻¹

- m = equilibrium coefficient
- N = dimensionless group, Eq. (28), or number of data pairs
- n = number of tanks in tanks-in-series model
- P = pressure of the gas phase, atm
- Pe = Peclet number, Eq. (27)
- Q = total tracer response integrated over all time
- t = time, s
- u = linear velocity of the liquid, ft·hr⁻¹
- w = dimensionless length, z/h
- X = x_e - x
- x = mole fraction of solute in the liquid phase
- y = mole fraction of solute in the gas phase
- z = axial coordinate, ft

• Greek Symbols

- σ = standard deviation
- θ = dimensionless time
- τ = mean residence time, s

• Subscripts

- e = equilibrium condition
- f = feed condition
- h = top of column
- G = gas phase
- L = liquid phase
- lm = log mean driving force, Eq. (36)
- 0 = bottom of column

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ChE book review

SEPARATIONS IN CHEMICAL ENGINEERING: EQUILIBRIUM STAGED OPERATIONS

by Phillip C. Wankat; Prentice Hall Publishing Co., 113 Silvan Ave., Englewood Cliffs, NJ 07632; 707 pages, \$47.50 (1988) (Formerly published by Elsevier Publishing Co.)

Reviewed by

Roseanne M. Ford
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Engineering analysis and design of the classical separation methods of distillation, absorption, and

Chemical Engineering Education

liquid-liquid extraction are covered in depth by Wankat's *Separations in Chemical Engineering: Equilibrium Staged Operations*.

This text has some excellent pedagogical qualities. It is easy to read, has clear detailed descriptions, and follows a logical progression which gradually builds on previous concepts. The development of problem-solving skills is emphasized throughout the text using a systematic approach (a modification of the strategy developed at McMaster University*) which follows six steps: 1) define the problem; 2) explore or think about it; 3) plan; 4) do it; 5) check; and 6) generalize. To reinforce the utility of this method, the example problems in the text are worked according to this procedure. This text would be very suitable for self-study. The level of sophistication is appropriate for sophomores, but may not appeal to senior-level students. A knowledge of calculus, material and energy balances, and phase equilibria is recommended. Mass transfer concepts are introduced only in Chapter 19 within the context of packed tower design.

Many problems are provided at the end of each chapter, some of which involve writing computer programs. They are divided into several categories: Discussion Problems, Generation of Alternatives, Derivations, Problems, More Complex Problems, Problems Requiring Other Resources, and Open-Ended and Synthesis Problems (a solution manual is available). A practical discussion of equipment design which includes correlations and heuristics is enhanced by some well-chosen photographs. However, the book lacks an Appendix containing the usual data tables necessary to make it a useful reference for design.

The text is comprised of nineteen chapters, the first fourteen of which are devoted to distillation. Chapter 1 defined an equilibrium stage process and a unit operation, and introduces the approach to problem solving. Vapor-liquid equilibria are reviewed in Chapter 2, including the conventional xy , T_{xy} , and H_{xy} graphical representations followed by dew point and bubble point calculations.

Rigorous calculations for flash distillation are presented in Chapter 3 for binary and multicomponent systems necessary for sizing the flash drum. Column distillation is initially introduced as a cascade of flash vaporizations in Chapter 4. Photographs of actual equipment convey a sense of the size and scale of a distillation tower. Possible flow regimes within the tower and their effect on the efficiency of separation are described. The concept of external material and energy balances is also introduced in Chapter 4.

Internal, stage-to-stage calculations are presented

* Woods, et al., *Eng. Ed.*, **66**, 238 (1975)

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in Chapter 5, according to the Lewis method, which assumes constant molal overflow. Chapter 6 covers the McCabe-Thiele graphical analysis, including many variations on the theme such as open steam, partial condensers, total reboilers, side streams, and intermediate reboilers and condensers. Limiting conditions, efficiencies, subcooled reflux, and superheated boil-up are also discussed.

Building upon this knowledge of binary systems, multicomponent distillation is described in the next

Continued on page 59.

Random Thoughts . . .

WHAT DO THEY KNOW, ANYWAY

2. Making Evaluations Effective

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Two columns ago^[1] I tried to persuade you that contrary to conventional faculty lounge wisdom, student evaluations provide reliable indicators of teaching quality: they correlate well with retrospective evaluations submitted by alumni and graduating seniors and tend to be higher for instructors whose students do best on common examinations. The question is not whether the evaluations mean anything—they clearly mean a lot—but how they should be structured to do the most good.

Following are some ideas for constructing, administering, and interpreting evaluations, starting with the simplest forms and proceeding to methods that take more work to implement but are more likely to improve teaching quality. For more suggestions and summaries of research on teaching evaluation, see Reference 2.

• *Collect overall course-end ratings of instruction.*

Rate the instruction you received in this course on a scale from 1 to 5, with 5 being the highest response.

Ratings of this sort are most effective when the numbers on the response scale are clearly defined. Definitions like "excellent," "above average," "fair," etc., don't do it; these terms are ambiguous and when they are used a very broad performance range tends to be lumped into "above average." You can get greater discrimination with a variation of the following instruction:

When responding, use as a basis of comparison all of your previous high school and college teachers. A response of 5 denotes one of the three or four best you've ever had; 4 = top 25%; 3 = 40-75%; 2 = bottom 40%; and 1 = one of the three or four worst you have ever had.



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

An instructor whose average rating is close to 5 on this scale is clearly doing a superb job and deserves nomination for an outstanding teacher award, and *serious* problems obviously exist if an instructor's rating is consistently close to 1. Ratings close to 4 indicate commendable teaching performance and ratings close to 2 suggest the need for corrective measures.

• *Collect ratings of individual aspects of instruction.*

To get the most out of a course-end evaluation, supplement the overall rating with ratings of specific aspects of teaching performance, such as clearly stating expectations, providing frequent examples, repeating difficult ideas, pointing out practical applications, answering questions thoroughly, preparing tests that reflect course content and emphasis, etc. (General questions about the instructor's preparedness and knowledge of the subject tend to be less useful.) The responses help identify areas of weakness and may provide ideas about how to improve teaching in the next course.

To be sure that the evaluations reflect a true cross-section of student opinion, administer and collect them in a single class session rather than counting on students to return them later. Results of evaluations for which the return rate is less than a minimal percentage should be re-

garded with deep suspicion: the recommended minimum is 50% (classes of 100 or more), 66% (50-100), 75% (20-50), and 80% (<20).^[2, p.89]

- **Collect evaluations midway through a course rather than waiting until the end.**

If the goal is to correct teaching problems and not just to identify them, find out what the problems are while enough time remains to do something about them. Ask open-ended questions on midcourse evaluations, leaving plenty of space for the responses:

1. *What do you like best about this course and/or the instructor? (List up to three things.)*
2. *What do you like least about the course and/or instructor? (List up to three things.)*
3. *If you were the instructor, what would you do to improve the course?*

- **Collect evaluations from small groups rather than from every student.**

One problem with individual evaluations is that many of the responses may reflect isolated gripes rather than widely held opinions. Another is that students may be fearful of offering negative criticism while a course is still in progress, even if the evaluations are anonymous (as they should be). A good way to counter both of these problems is to collect evaluations from groups of four or five students rather than from individuals. The students in a group should spend 5-10 minutes discussing the three questions given above and then prepare a collective evaluation that only includes points agreed upon by several group members.

- **Interview student representatives.**

Designate certain students as representatives of subgroups within the class. At one or more times during the semester, meet (or ask a colleague to meet) with the representatives to share the concerns of their constituents and to discuss possible measures to correct perceived problems. This procedure tends to generate constructive criticism at a level rarely attained through written evaluations and also gives students a greater sense that their opinions are valued.

- **Use a variety of sources of feedback.**

Collect retrospective teaching evaluations

from alumni and graduating seniors. Have faculty colleagues observe your teaching and provide feedback. Have one of your classes videotaped and review the tape (brace yourself—you may not be thrilled by everything you see).

- **Work with an instructional consultant to interpret student feedback and plan teaching improvement strategies.**

It is one thing to know that some students consider you a poor lecturer or think your tests are unfair and quite another to know what to do about it. Many universities have instructional consultants whose job is to help faculty members improve their teaching. These people can provide a variety of services, such as helping design and administer evaluation questionnaires, interviewing classes or groups of students about their perceptions of the instruction, observing and critiquing live or videotaped lectures, and working with instructors to help interpret evaluations and plan corrective strategies. If no one like this is available on your campus, ask a faculty colleague with a reputation as an outstanding teacher to work with you.

Can properly interpreted student feedback improve teaching? The research suggests that it does. In one study, instructors who received no feedback in the first half of a course received average end-of-term ratings in the 50th percentile of the population studied; instructors who received feedback scored in the 58th percentile; and instructors who got both feedback and instructional consultation scored in the 74th percentile.^[3] While midcourse evaluations are not guaranteed to improve course-end ratings and the teaching they reflect by that much, they are bound to have positive effects. A university, school, or department seeking to raise the level of its teaching program (e.g., as part of a TQM initiative) might well consider instituting midcourse evaluations and providing instructional consultation as a strong first step.

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THE OTHER THREE Rs

Rehearsal, Recitation, and ARgument

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Public speaking for undergraduates is rarely mentioned in engineering curriculum lists or discussions, yet the importance of clear and concise communication and presentation has probably never been greater. To address this need, some departments offer a one-term, one-unit oral presentation class to give students an opportunity for training in the presentation of technical papers. (A summary of our NCSU senior seminar course was recently published by Richard Felder.^[1])

The variety of circumstances where public speaking may be expected of our engineering graduates is considerable, ranging from short to long technical talks in conference or corporate meetings to participation on multipartisan panels in public meetings, and, even possibly, to the twenty-second to one-minute "sound bite" responses so common in televised or video-recorded conversations and interviews. In order to address this variety, as well as the controversial character and debate style implicit in some of the settings, the student must be challenged with a series of presentation opportunities, each in a distinctly different format.

Assuming that such a variety of presentations may provide both substance and spice, a one-semester senior course of one unit value has been given by the author with modest success. This paper summarizes the course content and its rationale and offers some reflections of both the students and the profes-

sor. Each class section has 6-8 students, with the senior class divided among as many faculty as are required. This group size works well for one-hour-per-week meetings on each of the presentation formats discussed below.

Student speakers customarily use overhead transparencies, which are easily prepared and can be enhanced by color at minimal cost and effort. Transparencies also fit well into late planning and reorganization of talks. The usual short litany of guidelines for overheads is given to the students at the outset: write legibly in large print, use only key words and phrases, use no more than one transparency every two minutes of allotted time, etc.

Audience attention and participation is achieved through a simple but effective requirement: at the end of the presentation, each audience member must ask a question of the speaker. This question/response mode is usually a bit artificial and stiff for the first one or two speakers, but the students soon begin posing substantive questions after each talk. The logic behind the demand for questions is simple: students learn more from a presentation when they are obligatory participants rather than mere observers—and the speaker enjoys the pleasure (or agony) of an attentive and responsive audience. After every presentation, I never ask questions, but I do provide each student with a written set of brief comments, including such items as extent of audience engagement, voice clarity, logic of organization, and quality and content of transparencies.

The presentation formats required of each student are

- informal brief (any topic)
- technical process description
- controversial topic (technical and/or non-technical)
- town meeting
- recitation (poem)

The purpose and form of these topics are as follows:



David F. Ollis is Distinguished Professor of Engineering at NCSU. He received his BS from Caltech, his MS from Northwestern, and his PhD from Stanford. He has worked at Texaco Process Research Laboratories and has presented or co-presented courses on chemical reactor design, biochemical engineering, and bioseparations. He is a coauthor of Biochemical Engineering Fundamentals (McGraw-Hill, 1986) and co-translator of Photochemical Technology (Wiley Interscience, 1991).

Informal Brief (1 period of 6-8 speakers) The student must present a five-minute talk, with or without transparencies or model, etc., on any topic of personal interest. The informal mode (no fixed presentation style) is a nice way to begin the semester and to have the students learn a bit about each other. It also provides the faculty member with a survey of the student's speaking talents. Speaker interest is normally high since the student can choose a topic for which he or she has considerable involvement and knowledge. Topics usually include "last summer's job" and "my favorite hobby," occasionally spiced by a presentation of "my favorite pet" (a ferret once assisted!), a campaign statement (pro-choice or pro-life), or a comment on biological evolution (all sides).

Technical Presentation (2 periods of 3-4 speakers each) The student must summarize a technical production process, including its historical development, current process flow diagrams, product uses, and prospects for the future. This is the only "straight-arrow" presentation of the semester. Each student chooses the process to be summarized and prepares all transparencies. I insist that there must be continuity in both the visual and oral presentations: the entire talk should appear logical to an audience member who can only see or only hear.

Controversial Topic (2 weeks for reading and preparation followed by two weeks for 3-4 presentations per allotted hour) In the old high school debate classes of the 1950s (long since abandoned), controversy and argument were center stage. A student had to prepare for both sides of a given question, since the point-of-view to be defended or attacked was unknown until just prior to the debate session. One motivation for this procedure was to test the speaker's knowledge of the subject from all sides.

To prepare for our class presentations, an assortment of books (dealing with controversial but often technical topics) is offered to the students, who are then asked to pick one, read it, and present a two-part summary to the class. The first part of the summary (approximately ten minutes) should outline the issue and the author's arguments and conclusions, following the author's version and words as closely as possible. The second part (a brief three-minute presentation) should be the student's critique of the author's approach, using the student's own words. The idea is to make the student present, clearly and distinctly, both the views of others and his or her own. Some students, perhaps numbed by the problem/solution/textbook approach which characterizes so much of our curriculum, appear reluctant to present a controversial subject in a public

I am always uncertain of the students' attitudes toward this assignment. The challenge is clearly one of presenting the author's view in only his or her own words—a situation foreign to the analyst/engineer.

forum. This method presents an opportunity to reverse that feeling. Some of the books we have used include Kennan's *The Nuclear Delusion*, Fallow's *National Defense*, Djerassi's *Politics of Contraception*, Ray's *Trashing the Planet*, Petroski's *To Engineer is Human*, Carson's *Silent Spring*, Meadow's *Limits to Growth*, Wade's *The Ultimate Experiment*, and Florman's *Existential Pleasures of Engineering*. These books are well-written and take strong positions. Most students find clear areas of agreement or disagreement with each author.

Town Meeting (1 week) "Resolved: that the State of North Carolina (Wake County, or City of Raleigh, as you prefer) will site, construct, and operate a hazardous waste incinerator." The students divide into three groups of two, representing industry, local government, and concerned citizens. The stances of these groups are naturally for, ambiguous about, and against the proposition, respectively. I usually choose a seventh, strong student to act as mediator.

To set the stage at the "meeting," one student briefly introduces the RCRA and TSCA statutes which motivate the development of such a resolution. Then one student in each group gives a partisan position summary (no questions; five minutes each for three presentations). A subsequent fifteen-minute pause allows each group to frame its rebuttal (blank transparencies and marking pens are provided). Following the presentation of rebuttals (two-minute maximum), I (representing the public at large) charge the mediator and the three groups to negotiate in good faith; then I leave the room for ten minutes.

Upon my return, the mediator presents any consensus position that has been developed. This is done most easily by indicating what each group will "win" from the outcome and how each group's primary concern will be addressed by the others. The challenge to the students is, "If you, as a collection of technically educated students, cannot reach any plausible and acceptable ground on this issue, how can you expect society at large to do any better?" The students usually see that seeking a win-win-win result works and that such an outcome should leave future relationships in far better shape than any do-or-die proposition which is too rigidly promoted.

Recitation (1 week) The easiest manner to test

whether a student knows *exactly* what to say is to hear a brief (approximately one minute) recitation of a poem. This recitation also provides the ultimate example of the claim that, with care and proper editing, any story or report can be fully presented in a very short period of time. It also helps the student see that poetry is successful because of its brevity and the ease with which the listener's mind constructs a full image from a few words. Who would not agree with such a characterization for Blake's

*Tiger, tiger, burning bright,
in the forest of the night.*

The use of images already familiar to a technical audience is also clearly a way to maximize impact and minimize delivery time.

Even with Blake and another example or two to lighten up the prospect of the following week's poem presentations, I am always uncertain of the students' attitudes toward this assignment. The challenge is clearly one of presenting the author's view in *only* his or her own words—a situation foreign to the analyst/engineer. Not surprisingly, most students fail to rehearse sufficiently to present an unhesitant, logically continual delivery. A bright spot is that nearly all students have favorite poems. My first year's group caught me off guard: half the class recited interesting poems which they had written in high school (not college) English!

Perhaps we should try the same approach with graduate students. Would not our somnolent AIChE and ACS meetings profit by an occasional poetic rendering? As an example, a graduate student might recite *Fame's Penny-Trumpet* (Lewis Carroll, 1869) with a prelude that is still relevant for the 1990s: "Affectionately dedicated to all 'original researchers' who 'pant' for endowment." For a partisan view, we could hardly do better than the closing stanzas:

*Deck your dull talk with pilfered shreds
of learning from a nobler time,
And oil each other's little heads
With mutual Flattery's golden slime:
And when the topmost height ye gain,
And stand in Glory's ether clear,
And grasp the prize of all your pain -
So many hundred pounds a year -
Then let Fame's banner be unfurled!
Sing Paeans for a victory won!
Ye tapers, that would light the worlds,
And cast a shadow on the Sun -
Who still shall pour His ray sublime,
One crystal flood, from East to West,
When ye have burned your little time
And flickered feebly into rest!*

Doubtless, the now-attentive audience would offer other views.

FEEDBACK

"We learn by doing" seems to characterize most student evaluations; while each general assignment seemed plausible at the outset, the students usually saw the presentation possibilities and purpose much more clearly in retrospect.

What else to add? A semester of these round-robin presentations has several times led to enough group coherence that a student skit was suggested, as was the inevitable roast of the professor. In deference to pending exams, these suggestions were tabled. Clearly, I underestimated the theatrical interests of the students. Their enthusiasm for additional opportunities suggested that they may have come to look forward to oral presentations. On the next round, we will try the skit (memorize your own words), after the poems.

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ChE book review

PROCESS DYNAMICS & CONTROL

by Dale E. Seborg, Thomas F. Edgar, and Duncan A. Mellichamp
John Wiley & Sons, New York (1989)

Reviewed by

Jeffrey C. Kantor

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Process control has been continuously evolving since its introduction in the chemical engineering curriculum during the late 1950s and early 1960s. Since then, each decade has been marked by a new textbook with significant market share. The 1965 book by Coughanowr and Koppel was perhaps the first of these. The market for this book was later split by the appearance of Luyben's book in 1973 and then largely supplanted in 1984 by Stephanopoulos.* The recent textbook by Seborg, Edgar, and Mellichamp

* By citing these, I don't mean to diminish the significant contributions of many others, including P. Buckley, N. Ceaglske, D. Eckman, P. Harriott, E. Johnson, D. Perlmutter, W. H. Ray, and T. Williams. These people and others wrote useful books that, for whatever reason, did not achieve broad acceptance as undergraduate course texts.

being reviewed here is clearly a successor to this list.

A Synopsis • This is a long and detailed book consisting of seven parts totaling 717 pages. The short first part describes motivations for process control, introduces block diagrams as a conceptual way to diagram the flow of information, and reviews aspects of process modeling. While there is a good bit of material here, one or two lectures should be enough for students familiar with dynamical modeling from their other coursework. The main point is that modeling for control purposes is different than modeling for process design or optimization. A different audience might spend more time reviewing this material at a more detailed level.

Part 2 of the book focuses on the transient behavior of linear system models. This is the part that contains the traditional detailed treatment of Laplace transforms, transfer functions, and the linearization of process models given as differential equations. This treatment does not reach for any high level of mathematical rigor, but it does include a rather complete discussion of how to execute the algebra for computing transforms and expanding by partial fractions. My students say that the discussion regarding linearization about an operating point is very helpful. Overall, these chapters are satisfactory from the point of view of the usual treatment of Laplace transforms. However, a course less mired in tradition could deemphasize the detail to focus more on the essential concepts of poles, zeros, and their qualitative effects on transient behavior.

Part 3 turns attention to the ideas of linear feedback control. Chapters 8 and 9 spend some time discussing practical issues of instrumentation and PID implementation. Subsequent chapters provide a conventional Laplace domain analysis of closed-loop stability, including the Routh condition, root locus, and some direct synthesis techniques. Relative to other books, an important addition in this text is the discussion of internal model control (IMC) in Chapter 12 and a comparison of IMC-inspired tuning rules with more traditional techniques such as Ziegler-Nichols and Cohen-Coon. Chapter 13 is a nuts-and-bolts chapter that covers much of what is needed to tune and troubleshoot an existing control loop. This part contains very applicable material, even though the theoretical connections between time and frequency domain analysis are not well elucidated.

Part 4 focuses on the frequency domain interpretation of the Laplace transform, with particular attention on the Bode plot, stability margins, and frequency domain identification. In my experience, students find this treatment repetitious of Part 3, and it

is not clear to them what practical advantage is gained. An instructor might wish to give an integrated presentation of the topics of Parts 3 and 4. In particular, I like to use the IMC framework as a starting point for the quantitative analysis of model uncertainty and its effects on closed-loop performance. Moreover, some of the advanced control techniques like time-delay compensation and prediction are much better treated from the IMC viewpoint. This approach, however, requires some supplementary materials.

Advanced control techniques are covered in Part 5. This includes a solid introductory treatment of multi-loop methods for feedforward design, relative gain array, and decoupling. Other important topics are discussed in a cursory way, including adaptive control, statistical quality control, and optimization. Also mentioned are expert systems, batch processes, and ladder logic. This is one of the few texts to even attempt to include some of this material, but at the level given, it would be difficult for instructors to build these topics into their courses in a detailed form.

Part 6 is an extensive, self-contained 170-page discussion of digital control techniques. On the positive side, a course emphasizing digital techniques could use this material as an alternative to Part 3. In a more balanced course, however, there is again a problem of duplication and repetitiousness. For example, some implementation details for PID control are described here for the third time in the book.

Part 7 concludes the book with an overview of developing control strategies for processing systems with examples. This is an ambitious goal, and it is certainly material that can bring a course to a solid conclusion, but there are only 27 pages devoted to it.

The book contains a substantial number of end-of-chapter problems. My students have found these well designed for the most part. The wide selection of problems makes it possible to give out different problem sets each year, which is one way to beat the dormitory filing systems.

Commentary • It is clear that this is an ambitious book containing a large amount of information—clearly too much to be covered in a single undergraduate course. The Preface makes clear that this was by design and suggests that the book be read in a "modular" fashion. Segments on the frequency domain and digital control, for example, could be omitted or included at the instructor's discretion.

My own feeling is that this sound practical goal

Continued on page 64.

SOLID PHASE EXTRACTION COLUMNS

A Tool for Teaching Biochromatography

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Biochromatography is difficult to teach to undergraduate students because it requires knowledge of molecular interactions not often covered in a typical undergraduate curriculum. But with up to sixty percent of the total protein manufacturing cost directly related to the purification process, a basic knowledge of biochromatography and its inherent efficiencies is an essential part of the biochemical engineer's education. Class lectures on the subject attempt to explain and diagram column dynamics, but hands-on experience will help the students grasp the concepts and remember them far longer. Thus, we have developed two laboratory experiments for protein chromatography.

The experiments were designed to require minimal and inexpensive equipment and to be performed within a two-hour laboratory period. The students were each given three 1 ml Bakerbond spe™ columns (cationic, anionic, and hydrophobic interaction), a size-exclusion column, and an unknown protein or mixture of proteins. Based on the binding and elution properties of the proteins and the known physicochemical properties of several possible protein candidates (pI and relative hydrophobicity), the students were asked to determine which protein(s) were present. Colored proteins were chosen as the unknowns so that no special detection equipment was required.

THEORY

A mixture of proteins can be separated with the use of chromatographic techniques based on the ten-

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dency of the various proteins to adsorb to the column packing. In ion-exchange chromatography, adsorption of proteins depends on the proteins' isoelectric point relative to the column pH. Proteins with a high isoelectric point will bind tightly to a cation exchange column in the presence of a low pH and a low salt concentration. Proteins with a low isoelectric point will bind tightly to an anion exchange column in the presence of a high pH and a low salt concentration.

Hydrophobic interaction chromatography uses a high salt concentration to induce an interaction between hydrophobic regions of a protein and a weakly hydrophobic column packing. In all three cases, elution of the bound proteins can be achieved using a salt gradient.

Another type of chromatography, size-exclusion chromatography, separates molecules based on their relative size. The column is filled with a packing with a specific pore size distribution. Smaller molecules enter the pores and linger inside them, while larger molecules, which cannot fit into the pores, pass more rapidly through the column.

Bakerbond spe Wide-Pore columns are small (12 x 65 mm) reusable polypropylene tubes (6 ml total

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Phillipsburg, NJ 08865

In their laboratory reports, the students showed that they recognized that the Gaussian distribution of the pore size for size-exclusion chromatography has an effect on the column resolution, and they noted that protein shape could also have an effect. Several students took their observations one step further and applied them to separation problems that might be encountered in industry.

volume) which contain 500 mg (1.5 ml) of 40-mm silica-based stationary phases. These inexpensive columns are designed to be used for sample preparation prior to conventional open column chromatography or high-performance liquid chromatography (HPLC), and can also be used to determine the physicochemical properties of a particular "target" protein as well as its retention behavior on various chromatographic matrices. The available stationary-phase surface chemistries include Bakerbond Wide-Pore BUTYL (-C₄, reversed-phase matrix), Bakerbond Wide-Pore CBX (-COO⁻, weak-cation exchanger), Bakerbond Wide-Pore PEI (-NH₃⁺, weak-anion exchanger), Bakerbond Wide-Pore HI-Propyl (-C₃, hydrophobic-interaction matrix), and Sephadex™ G-25 (size-exclusion matrix). Solid phase extraction columns are available from other manufacturers, but have not been tested with these experiments.

Scale-up of chromatography columns for protein separation and purification is an important issue for biochemical engineers designing a process. The purest product is obtained with a minimum band width for each protein. Various forces influence the band width, or zone spreading, such as longitudinal diffusion, eddy diffusion, and the lack of a local equilibrium at the front and rear of the band. These forces can be modeled by assuming the molecules move through the column according to the random-walk theory (the molecules move in a series of random steps and starts). A Gaussian distribution of the molecules is also assumed, with $\sigma = 1\sqrt{n}$, where n is the number of random-walk steps and l is the step length. The resulting model^[1,2] is

$$H = \frac{\sigma^2}{L} = \frac{B}{\bar{u}} + A + C_s \bar{u} + C_m \bar{u} \quad (1)$$

TABLE 1
Material Data^[4]

Protein	MW (kDa)	pI	relative hydrophobicity*
Bovine serum albumin	69.0	5.1	20.5
α-Chymotrypsin	21.6	8.6	16.6
α-Chymotrypsinogen	25.0	9.2	18.1
Conalbumin	77.0	6.3	6.3
Cytochrome C	12.2	9.4	0.6
Ferritin	500.0	4.3	20.8
β-Glucosidase	130.3	7.3	15.6
Hemoglobin	64.0	7.0	1.1**
Lactoperoxidase	85.0	9.5	19.5
Lysozyme	13.9	11.0	8.5
Myoglobin	17.5	7.1	0.8
Ovalbumin	43.5	4.7	6.5
Ribonuclease A	13.5	8.7	1.6
Dyes			
Phenol red	0.35		
Erioglaucine blue	0.78		
Column Packings			
Sephadex G-10	<0.7 kDa)		
Sephadex G-50	(1.5 to 30 kDa)		
Sephadex G-75	(3 to 70 kDa)		
Sephadex G-100	(4 to 150 kDa)		

* Higher values are more hydrophobic
** Estimated

where

$H = \frac{\sigma^2}{L}$ represents the plate height, used to express the net effect of zone spreading

$\frac{B}{\bar{u}}$ = longitudinal diffusion

A = eddy diffusion

$C_s \bar{u}$ = resistance to mass transfer at the solute-stationary phase interface

$C_m \bar{u}$ = resistance to radial mass transfer caused by particles of the packing material

The magnitude of each of these effects is determined by the velocity of the sample (\bar{u}) in the column. If the velocity is too high, the mass transfer resistances predominate and there is more band spreading. If the velocity is too low, the longitudinal diffusion increases the band width. Therefore, there is an optimal sample velocity for each mixture of proteins.

The resolution of two peaks, R, is defined as the distance between the peaks divided by

the average width

$$R = \frac{t_{RB} - t_{RA}}{0.5(t_{WA} + t_{WB})} \quad (2)$$

where

t_{RB}, t_{RA} = retention times of components A and B

t_{WA}, t_{WB} = width of peak A and peak B

In column chromatography, peaks become broader proportional to the square root of the column length, but their separation increases in direct proportion to the column length.^[3] Thus the resolution is proportional to the square root of the column length. This means that to double the separation between two

bands, a column four times as long is required.

These scale-up concepts, when explained in a class lecture, are not always intuitively obvious to the undergraduate student. Varying these factors in a laboratory exercise, however, allows the students to observe the effects of the column length and sample velocity on the degree of separation.

EXPERIMENT PROCEDURE

Each student is given molecular weight, isoelectric point, and relative hydrophobicity data on a variety of proteins, and size data on two dyes as well as four types of Sephadex that will be used (see Table 1). They are also given the necessary buffers (Table 2), 3 Bakerbond spe columns (WP PEI, WP HI-Propyl, and WP CBX), and a column for size-exclusion chromatography. The students are to process the unknowns through the various columns and determine their identity. The samples can be pulled through the spe columns using a vacuum system or forced through the spe columns using compressed air. In order to use the laboratory time efficiently (to make sure the students have thought about chromatography concepts before lab time) the homework assignment shown in Table 3 is given the week before the experiments.

Chromatography Lab 1

Each student is given a single unknown protein (chosen from the list in Table 4) and a mixture of two or three of these proteins, each dissolved in buffers at both pH 6 and pH 7.5. The Bakerbond spe columns must first be equilibrated to the correct pH by passing 5 to 10 ml of buffer through the column before any protein samples are added. When the column eluant is at the correct pH, about 0.2 ml of protein

TABLE 2
Solutions

20 mM	KH_2PO_4	pH 6 and pH 7.5
1M	Na_2SO_4	
2M	Na_2SO_4	
200 mM	KH_2PO_4	pH 7
500 mM	KH_2PO_4	pH 7

sample is added to the column. The students slowly process the protein samples through each of the three Bakerbond spe columns and visually observe whether or not binding occurs. By comparing their observations with the table they completed in the homework assignment, the protein(s) can be identified. Proteins can be eluted from the column (and the column cleaned before introducing the next sample) by running a salt solution (200 or 500 mM) through the column.

Chromatography Lab 2

This laboratory exercise has two goals: (1) to determine whether an unknown sample contains ferritin, hemoglobin, cytochrome C and/or a dye, and (2) to determine the effects of the column length and sample velocity on the resolution of the mixture. Each student is given an empty column, a mixture of protein and/or dye, and small quantities of the

TABLE 3
Homework Assignment

In order to prepare for next week's laboratory session, you must fill out the table below. Use a "+" sign to indicate binding and a "-" sign to indicate that the protein will flow through the column without binding. This will help you determine which protein(s) you have in the laboratory assignment. Also consider under what conditions the proteins would elute.

Column Conditions:

- CATION EXCHANGER: Equilibrate column with pH 6 buffer
- ANION EXCHANGER: Equilibrate column with pH 7.5 buffer
- HIC: Equilibrate column with 1 M salt solution (assume 6.1 relative hydrophobicity)

Protein	COLUMN TYPE			
	Cation Exchange	Anion Exchange	HIC	Sephadex G-10 G-50 G-75 G-100
Bovine serum albumin				
α -Chymotrypsin				
α -Chymotrypsinogen				
Conalbumin				
Cytochrome C				
Ferritin				
β -Glucosidase				
Hemoglobin				
Lactoperoxidase				
Lysozyme				
Myoglobin				
Ovalbumin				
Ribonuclease A				
Phenol red				
Erioglaucine blue				

What mixtures of proteins could not be separated by any combination of the columns and conditions above?

four types of Sephadex gels. Before starting the experiment, the Sephadex beads must be swollen in 20 mM salt solution. The beads should be poured carefully into the column, so that cracks and holes in the packing are avoided. In addition, the column should not be allowed to become dry during the course of the experiment.

To accomplish the first goal, the sample is processed through similar columns filled with different sizes of Sephadex. The students choose which sizes to use in order to determine what protein/dye combination is in their sample. For at least two different sizes of beads, the students observe whether the compounds pass quickly through the columns or stay near the top of the column. From their observations they can identify the unknowns in the mixture. To observe scale-up effects, only one size of Sephadex is used (one that separated the student's unknown into two bands). Samples are processed under four conditions: (1) short column (2 cm) and gravity flow; (2) short column and vacuum-induced flow; (3) long column (8 cm) and gravity flow; and (4) long column and vacuum-induced flow. The students can easily observe the effects of column length and sample velocity on the degree of separation.

The results of this experiment can be quantified by collecting samples of the eluant and measuring the absorbance with a spectrophotometer. The students can then produce a chromatogram and calculate the resolution under the different conditions.

CONCLUSIONS

The students found the labs relatively uncomplicated and possible to complete within the two-hour laboratory period. The use of colored proteins allowed them to actually observe the "binding" rather than simply studying a chromatogram that comes from a spectrophotometer. The students did request that proteins of different colors be used in the exercise (all of the proteins used are brown or reddish-brown) so that they could confirm their deductions based on color observation. By limiting the proteins to one color, however, the students were forced to determine the protein identity based on

adsorption properties, not on color. By the end of the first laboratory exercise the students had a clearer idea of how proteins could be separated based on differing isoelectric points. Properties of size-exclusion chromatography were understood after the first half of the second experiment. Several students commented on the unexpected property exhibited by the smaller dye molecules which moved more slowly than the larger protein molecules through the size-exclusion column—a concept not easily grasped in class lectures.

Consequences of scale-up, such as the effects of velocity and column length on zone spreading (band width) were similarly difficult to comprehend during the lecture, but were very clear when observed firsthand. In their laboratory reports, the students showed that they recognized that the Gaussian distribution of the pore size for size-exclusion chromatography has an effect on the column resolution, and they noted that protein shape could also have an effect. Several students took their observations one step further and applied them to separation problems that might be encountered in industry, suggesting changes that would have to be made.

It is important that the theoretical concepts be explained in class before the students attempt the laboratory exercises. Operational problems also became clear while the students were performing the experiments. For example, the importance of equilibrating the column before introducing samples was discovered by several students who found that none of the proteins would bind to their column if it had not been equilibrated. The problems that occur when the column is allowed to become dry (cracks or holes in the packing) were noted by several students performing size-exclusion chromatography.

The students rated the laboratory experiment highly and as "very worthwhile." It allowed them to perform and validate what they had learned in class. They were able to use chromatography techniques and to more clearly understand the interaction of protein properties and column phases.

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□

Conalbumin	50 mg/ml
Cytochrome C	20 mg/ml
Hemoglobin	20 mg/ml
Ferritin	20 mg/ml

COLLABORATIVE STUDY GROUPS

A Learning Aid in Chemical Engineering

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Towards the end of the 1990 academic year, I introduced a system of collaborative study groups into a foundation course in chemical engineering—it proved to be the most exciting thing I have done in my twelve years as a teacher. Apart from the excitement of seeing how well the system worked, it was also the first innovative teaching technique I have found that is actually less work for everyone concerned. The course, "Chemical Process Analysis" (CPA), is taken in the second year of study for a four-year degree in chemical engineering. It lasts two semesters and covers basic material and energy balances in addition to computation and chemical process industries.^[1]

The pressures which drove me to do something are evident in Figures 1 and 2. They show the increasing size of our second-year class, as well as its changing composition. The figures show students classified according to racial background because until lately the educational system in South Africa has been divided along those lines. The categories used in the figures are white, other (colored and Indian), and African.

The inequalities of resources and teaching qualifications have meant that non-white students have been disadvantaged to a greater or lesser degree relative to the white students. The result of the educational disadvantage has been reflected in the pass rates in the CPA course: from 1986 to 1990, 81% of the white students passed CPA, while only 52% of the "other" students and 39% of the

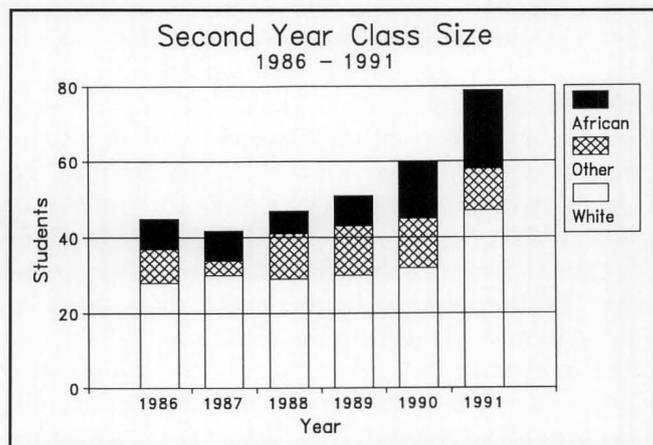


Figure 1. Second-year class size.

African students passed.

I have yet to fully exploit the potential of this system, nor do I claim to understand all that is involved; but here is what I did and why it seemed to work so effectively.

BACKGROUND

Over the past few years I have been grappling with how best to cope with the increasing proportion of disadvantaged students in CPA and their poor success in the course. My first attempt was to set up special tutorials for students who were struggling, but this was only marginally helpful, largely because it added extra work for those who were already having trouble. Our department then decided to commit more tutors to the regular tutorials in the course so that extra help could be given to those who needed it. But even this had little effect in improving the success rate of disadvantaged students.

The tutorial system we were using at this stage was one in which the students were given a set of problems to work on and hand in, with one afternoon per week set aside when they could receive help on the problems. Attendance at the help sessions was voluntary, and one-half to two-thirds of the class generally attended for at least part of the afternoon. Students were encouraged to work on the problems

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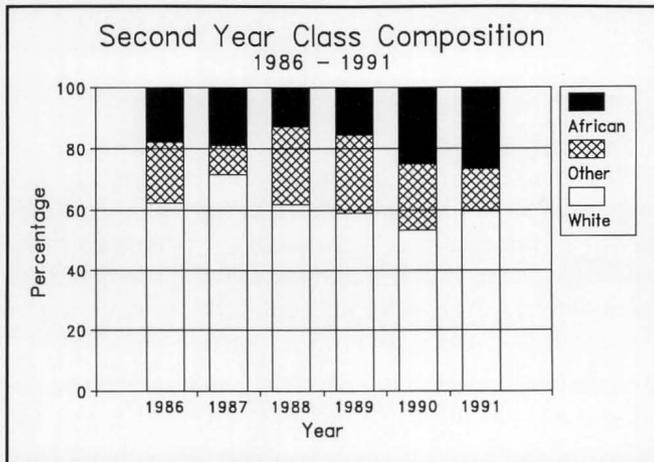


Figure 2. Second-year class composition.

ahead of time so they could come to the tutorial sessions for specific help in areas where they had encountered trouble. Generally, less than half the students took this approach; the rest came unprepared and only began work on the problems at the last possible moment. Typically, if two weeks were given for a set of problems, most students waited until the last week to begin work on it.

While struggling to solve this situation, in mid-1990 Professor Andrew Sass of ASPECT (a special academic support program for disadvantaged engineering students) introduced me to the concept of collaborative study groups. Landis in fact contends that a system of structured collaborative (co-operative) study groups is one of the key features required for a successful minority program.^[2] I immediately saw that this might be a solution to the problems I was facing and trying to resolve.

The system which we eventually designed differs from the workshop program developed by Treisman at Berkeley (and since implemented by others) which generally involves minority students doing additional and more complex problems and where a high level of preparation is expected of the students.^[2-5] My previous experiences prompted me to include the whole class in the exercise, to enable all to benefit from it, as has apparently been done elsewhere,^[6] without adding extra work on any of them.

STARTING OFF

I discussed the idea of collaborative study groups with the class, and together we hammered out the details of running the system. Many of the students were opposed to the scheme—particularly the better students, who were concerned about having to spend more time on the course and were unwilling to "carry" the weaker students.

Winter 1993

In the end we agreed that we would experiment, largely for the sake of the students who were struggling. I would compose the groups on the basis of student preferences. I would assign simple problems that could be worked beforehand and would give problems for each session as the students arrived. These last problems would have to be completed during that session. Each student would have to submit his/her own solutions to the problems to ensure that each had done the work, with or without help from the group.

I introduced a system of collaborative study groups into a foundation course—it proved to be the most exciting thing I have done . . . it was also the first innovative teaching technique I have found that is actually less work for everyone concerned.

This first class had been together for the preceding six months and had had previous experience in group work through a design project earlier in the year. Some of the groups consisted of students who all wanted to work with each other, but others were more difficult to compose. In the end I had to appoint some groups comprising only the class "loners." Each group generally had a spread of abilities among its members, either towards the top, middle, or bottom of the class (*i.e.*, students chose to work with others of similar abilities).

As the students tackled the assigned problems that first afternoon, I soon sensed an excitement in the class. Although I gave them a break at mid-afternoon, many of them worked right through, and at the end of the session one student even commented that he had never realized he could work for a solid three hours. Altogether, I ran four of these kind of sessions with the 1990 class. Feedback was positive—even from those who were originally opposed to the idea. All of the students found that they spent less time than they would normally have spent on solving problems, partly because through the group approach to a problem they could discover and avoid silly arithmetic mistakes.

While the group plan was introduced too late in the year to have a significant effect on the students' success, they felt that it was so beneficial to them that they asked that it be repeated in their courses the following year. The second time around, when it was used for the whole year, there was a marked improvement in the pass rate for the course (detailed at the end of this paper).

PROBLEMS

There are problems which need to be addressed. The first is the constitution of the groups. The first time I used the system I noticed that the larger groups of five or six students worked better than the smaller groups of four. This was in spite of the fact that the larger groups often split into smaller groups of two or three. The reason for this seems to be that a critical mass is needed for a group to work effectively. Another factor could have been that most of the smaller groups were comprised of the "loners" in the class. I thought that they would be better off in a group together where they would not be overwhelmed by the others, but that may have been the wrong decision.

In 1991 I again observed that the smaller groups did not work as effectively, even though in this case they were not groups of loners. In fact, one of the groups started off with six members and was reduced when some of its members left the course. This supports my contention that a critical mass is necessary.

The larger the class is, the more difficult it is to form the groups. I experienced this in 1991 with a class of eighty instead of the sixty that made up the 1990 class. It is also more difficult to constitute groups where the students feel comfortable when the members of a class do not know each other initially. Another factor that I felt had to be considered was that weaker groups needed to be reinforced by including some of the better students in them. In the 1991 class, most of the self-appointed groups had a larger spread of abilities, and I was careful to group the remaining students in like manner, avoiding groups made up of only weaker students.

There has not been any problem in getting students to work together in this manner. Only a few students isolated themselves from their groups, and there was no significant copying from others in the groups. Some groups of disadvantaged students did not readily interact with one another at the beginning, but this was overcome by simply encouraging them to work together (and exciting to see how they changed).

Another problem was how to determine exactly what an average student could reasonably achieve in one afternoon, but this will become easier to determine as we gain more experience in running these sessions. At times I have had to let the students complete some problems at home; but this is not necessarily a bad thing.

Some instructors may have difficulty finding a suitable environment for accommodated a class such as this one. It is essential that each group be able to sit

around a table to work, which is impossible in most lecture theaters. I was fortunate in have a suitable flat design room which could be used.

BENEFITS

The benefits of an approach such as this are numerous. The first direct benefit for me was the immediate reinforcement of lectures in the problems tackled, relative to our previous system. This could be achieved in other ways without collaborative study groups, but it was a by-product for us.

Another benefit is that staff time is used more effectively—especially important in view of the increasing academic pressures. Staff can concentrate on the more serious problems which the students cannot jointly resolve in their groups. The result is that students with serious problems have more direct access to the best help since the lecturer is not tied up with trivial problems. Moreover, senior staff can be available to a whole class at once. I have also found that I need fewer tutors.

Student time is also used more effectively since they are able to immediately solve their difficulties in a group setting of collaboration rather than struggling for long periods of time on their own. Marking tutorials become more efficient in that the solutions from each group are generally the same. This means that the instructor can concentrate on conceptual problems and can more readily identify common difficulties.

The system encourages peer-group learning and helps students to build helpful working relationships with others in the class. This is particularly important for students who by their circumstances or nature have difficulty in forming relationships outside of regular classes. It also breaks down the dichotomy found in many minority students between their work and their peer relationships, which Treisman found was a key factor in their failure.^[6,7] I would rate this as one of the most significant educational benefits from the collaborative study group system. It is also in accord with the emphasis placed by Landis on collaborative study.^[2]

Another benefit is that students learn to communicate with one another on a technical level, which is very important for aspiring chemical engineers. This was noted by Hudspeth in the academic excellence workshops run at California State Polytechnic University,^[3,5,8] as well as being one of the reasons Landis used to encourage students to work in such groups.

An additional advantage is that the problems from previous years can be re-used since students work the solutions on their own in class and do not copy the

solutions. This is particularly helpful when there are significant numbers of repeating students in the class (as was the case in this course).

The second time I taught these sessions I realized that most students were not solving the straightforward problems I gave them as preparation, which meant that they were taking too long coping with the more complex problems. I rectified this by assigning a straightforward problem first off, and it had the desired benefit of enabling them to handle the more difficult problems that were assigned later.

With students working in groups there is also the potential to pose problems which require interaction and which cannot be solved alone. I have yet to exploit this potential.

ESSENTIAL FEATURES

The following key elements can be identified as essential features of the collaborative study group system. I doubt whether the system would work if any one of the features was missing.

- Students work in groups but produce their own solutions to the problems.
- The groups are chosen on the basis of student preferences, subject to the constraint that each student must be part of a group.
- The groups are large enough to allow for significant interaction between the members, but not so large as to be unwieldy (six members per group seems to be optimum).
- Attendance at group problem-solving sessions is compulsory. (This is done by making it a requirement for entry to the examination.)
- The groups work together on the problems. (Students who like to streak ahead are discouraged from doing so, as are those who want to work entirely on their own.)
- The groups work around a common table. (A group of six working in a row does not allow for meaningful interaction.)

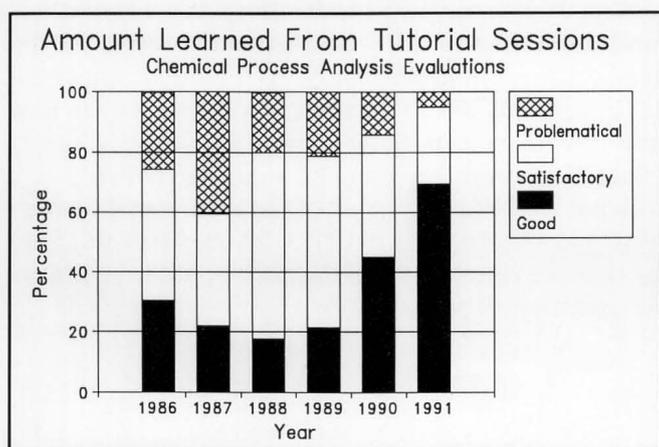


Figure 3. Student evaluation of tutorial sessions.

- The problems assigned are not known by the students beforehand (allowing the session to become a shared experience, which generates much of the excitement).
- Solutions to the problems must be handed in by the end of the session. (This makes the students get on with the job; there has been some flexibility as to how much must be completed).
- The system was adapted from similar systems used elsewhere, in consultation with the students themselves.

OUTCOME

Figure 3 shows the response in course evaluations to the question concerning the amount learned from tutorial sessions. The effect of the few group sessions run in 1990 can be clearly seen in the increase of those responding positively, compared to previous years, with a concomitant decrease in negative responses. There was further improvement in these responses in 1991 (when the collaborative study group system was used for the whole course), with 69% responding favorably and only 5% indicating that they had problems.

In 1991 the pass rate for the course improved as follows: for the white students it increased by 15%; for the disadvantaged students, 65%; and for the class as a whole, by 28%.^[9] This is a clear indication of the general educational benefit of collaborative study groups, as well as the special benefit derived by disadvantaged students.

Judging from the student reaction and by the improved pass rates for the course, the system of collaborative study groups was a success. One of the secrets of its success was that the system structure was jointly forged by the students and the instructor. This meant that the next group of students also accepted the system well in spite of not having been involved in its formulation.

The challenge for me as instructor is to be creative in how I use the system. But I am convinced that even if I simply use the same problems that I have already used, the students will still be much better off than they were under the prior scheme. It took a good amount of courage to implement the system the first time, but that courage was amply rewarded. I strongly encourage others to try something similar, even if only a single period is available for this sort of exercise instead of a whole afternoon. It can still have a lasting impact on the way in which students learn.

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

SOLVING CHEMICAL KINETICS PROBLEMS BY THE MARKOV-CHAIN APPROACH

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Imagine the following scene: you are correcting a quiz given to students in your (say) second year chemical kinetics course. You assigned the problem of a homogeneous mixture containing initially 1 mole of species A and 0.2 moles of species B. $A \rightleftharpoons B$ reactions are by no means imaginary; the classical gas-phase reaction between ortho- H_2 and para- H_2 ,^[1] and the liquid-phase hydrolysis of lactone to γ -hydroxybutyric acid in strong hydrochloric acid solutions^[2] are two real-life examples. In every minute, 75 mole % of A are converted to B, and 5% of B converted to A. How many moles of A and B are present in the mixture at one and two minutes after the process has started, and what is the final (equilibrium) composition?

You are trudging your way through a motley collection of answers based on more-or-less successful attempts by your students to set up the conventional differential rate equation and to integrate them somehow. Your boredom threatens to reach unprecedented depths—when suddenly you come across the unexpected. One of your students almost obtained the right answers . . . without writing down a single rate equation.

Congratulations! This student of yours apparently recognized that the reaction process may be interpreted as a Markov chain in the theory of stochastic processes. Composition is considered as a probability (state) vector and the rate constants as transitional



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probabilities; the final composition is given by a straightforward application of the eigenvalue problem in linear algebra. For want of numerical carefulness, the answers are slightly off. Never mind—give this student an A⁺ for leaving behind the conventional, the obvious, the unimaginative!

THE CHEMICAL REACTION AS A MARKOV CHAIN

The key to this off-the-beaten-path approach is that the amounts of species A and B present at the $(n+1)^{\text{st}}$ time unit depend only on their amounts at the n^{th} time unit. Calling the amounts states, we can now say that transition between two consecutive (adjacent) states is independent of transition between any other states. We may think of the transition between states as a probability matrix with its elements given by the rate constants which, in turn, are interpreted as transitional probabilities.

The Markov chain model of the reaction is

$$A(n+1) = 0.25 A(n) + 0.05 B(n) \quad (1a)$$

$$B(n+1) = 0.75 A(n) + 0.95 B(n) \quad (1b)$$

with $A(0) = 1$ and $B(0) = 0.2$. The transition matrix

(Markov matrix) is

$$\mathbf{P} = \begin{pmatrix} 0.25 & 0.05 \\ 0.75 & 0.95 \end{pmatrix} \quad (2)$$

and the state vector

$$\mathbf{p}_n = \begin{pmatrix} A(n) \\ B(n) \end{pmatrix} = \mathbf{P}^n \mathbf{p}_0 \quad (3)$$

yields the time-dependent concentrations. Numerically (in moles), the solution vectors after one minute and two minutes are

$$\begin{pmatrix} A(1) \\ B(1) \end{pmatrix} = \begin{pmatrix} 0.25 & 0.05 \\ 0.75 & 0.95 \end{pmatrix} \begin{pmatrix} 1 \\ 0.2 \end{pmatrix} = \begin{pmatrix} 0.26 \\ 0.94 \end{pmatrix}$$

and

$$\begin{pmatrix} A(2) \\ B(2) \end{pmatrix} = \begin{pmatrix} 0.25 & 0.05 \\ 0.75 & 0.95 \end{pmatrix} \begin{pmatrix} 0.26 \\ 0.94 \end{pmatrix} = \begin{pmatrix} 0.112 \\ 1.088 \end{pmatrix}$$

The conventional, and more time-consuming, method is to solve the differential rate equations

$$\begin{aligned} \frac{dA}{dt} &= -0.75A + 0.05B \\ \frac{dB}{dt} &= 0.75A - 0.05B \end{aligned}$$

which yield

$$\begin{aligned} A(t) &= 0.075 + 0.925 \exp(-0.8t) \\ B(t) &= 1.125 - 0.925 \exp(-0.8t) \end{aligned}$$

The equilibrium concentrations are found via the

$$\lim_{n \rightarrow \infty} \mathbf{p}_n = \mathbf{p}^* = \text{const. property of the chain}$$

which implies the relationship

$$\mathbf{P} \mathbf{p}^* = \mathbf{p}^* \quad (4)$$

e.g., an eigenvalue problem with eigenvalue of unity. In our case, Eq. (4) is

$$\begin{pmatrix} 0.25 & 0.05 \\ 0.75 & 0.95 \end{pmatrix} \begin{pmatrix} p_1^* \\ p_2^* \end{pmatrix} = \begin{pmatrix} p_1^* \\ p_2^* \end{pmatrix}$$

which yields an eigenvector

$$\begin{pmatrix} 1 \\ 15 \end{pmatrix} k$$

where k is an arbitrary real constant. If k is chosen as the "normalizer" value

$$\frac{(A_0 + B_0)}{(1 + 15)} = \frac{1.2}{16}$$

the equilibrium values $A^* = 1.2/16 = 0.075$ mol and $B^* = (1.2)(15)/16 = 1.125$ mol are found immediately.

The attractiveness of the Markov-chain approach increases with the number of reacting components, *e.g.*, the dimensionality of the problem. Suppose that three components A, B, C react in a mixture with
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differential rate equations

$$\begin{aligned} \frac{dA}{dt} &= -0.3A + 0.1B \\ \frac{dB}{dt} &= 0.2A - 0.3B + 0.1C \\ \frac{dC}{dt} &= 0.1A + 0.2B - 0.1C \end{aligned}$$

with initial composition $A_0 = 1$, $B_0 = 0.6$, and $C_0 = 0.3$ mol. In the Markovian approach

$$\mathbf{p}_n = \begin{pmatrix} 0.7 & 0.1 & 0.0 \\ 0.2 & 0.7 & 0.1 \\ 0.1 & 0.2 & 0.9 \end{pmatrix} \mathbf{p}_{n-1} = \begin{pmatrix} 0.7 & 0.1 & 0.0 \\ 0.2 & 0.7 & 0.1 \\ 0.1 & 0.2 & 0.9 \end{pmatrix}^n \begin{pmatrix} 1 \\ 0.6 \\ 0.3 \end{pmatrix} \quad (5)$$

represents the state of the reaction mixture of each time instant. The eigenvector associated with equilibrium has the elements (1, 3, 7), and $k = 2/11$ is the normalizer yielding the equilibrium concentrations $A^* = 0.1818$, $B^* = 0.5454$, and $C^* = 1.2727$ mol. The handling of the equilibrium state does not require, of course, the solution of the differential rate equations, but the manipulations of the algebraic equation set obtained by equating the concentration derivatives to zero are not simpler than the computation of the eigenvector.

The didactic value of the Markov-chain path of solution lies not only in its simplicity and elegance, but also 1) in demonstrating the power of probability theory in handling *a priori* deterministic problems, and 2) in applying fundamental tenets of linear algebra to tangible physical problems of practical importance. Undergraduate students in engineering usually regard linear algebra as an esoteric nuisance (the student in this story is a rare bird, indeed!); treating chemical kinetics problems with appropriate techniques of linear algebra proves the opposite.

The power of Markovian thinking is much wider than what is presented here. Physics, biology, economics, communications, and computer networks are well-known areas of application. The interested reader will find references 3-5 useful for further exploration.

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FLUID STRUCTURE FOR SOPHOMORES

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Whenever new fields of technology are developed, they will involve atoms and molecules. Those will have to be manipulated on a large scale, and that will mean that chemical engineering will be involved — inevitably.

Isaac Asimov (1988)

The undergraduate course in chemical engineering thermodynamics continues to present teaching challenges despite its long-term presence in the curriculum. Students often complain that it seems "too esoteric." But it is also a course that can provide opportunities for giving students a strong sense of "manipulating molecules" by illustrating the development of engineering models which address molecular scale interactions. Then students might say that "it was especially good as an introduction to engineering,"—and what a healthy shift in perception that would be. The approach advocated here is to integrate the esoteric principles with the students' inherent intuition so they can see all levels of the modeling process.

This general approach may seem obvious, but introducing fluid structure as a means of reducing the esoteric perception is probably not so obvious. There always seems to be more subject matter than there is time to cover it, and as a result there is a tendency to reduce thermodynamics to its smallest kernel of unique and general concepts (Maxwell's relations and the Gibbs-Duhem equation, for instance). Focusing so much on those concepts, however, would be too esoteric—by themselves, these concepts do not help students understand how liquefaction or distillation works or why polymer blending rarely works. Clearly, there must be some additional relations which demonstrate the utility of the "pure thermodynamics." We faculty recognize these as constitutive relations like equations of state or Gibbs excess functions, and when pressed for time it is tempting to present them macroscopically, as empirical relations that should

basically be accepted on faith. In the discussion below, an alternative strategy is presented which takes advantage of common roots in the molecular perspective to rapidly generate the constitutive relations in a way that highlights some great engineering models and simultaneously leads to the kind of molecular perspective that Asimov envisions.

The common root of constitutive relations is the fluid structure. For solution models, we apply the energy equation (Eq. 1). For the equation of state, we apply the pressure equation (Eq. 2). But in all cases we add up the local quantity (energy or force) weighted by the local density. The local energy or force field around an atom is clear to students from introductory chemistry and physics. The various potential models and the types of molecules they describe are reviewed during the first week of class. But the "fluid structure," which describes the local density, sounds at first like an esoteric concept at its worst. Building an appreciation of fluid structure is a delicate undertaking, but once this appreciation is established, a single framework can be repeatedly applied for rapidly reducing to practical application. Our approach is detailed below.

The concept of fluid structure does for energy what the concept of particle distribution in boxes does for entropy; it provides the connection to the molecular scale. For the treatment of particle distribution in boxes we adapt the presentation of Balzhiser, *et al.*,^[1] at the same time that entropy is introduced. Thus, the students are ready and waiting for a



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molecular formulation of the complete problem and are anxious for applications.

The presentation below emphasizes the development of the principles of thermodynamic modeling in four stages. First, a brief introduction to how the fluid structure influences the macroscopic properties is given by the energy equation and the pressure equation. Second, the qualitative features of fluid structure are developed for several examples through simple intuitive arguments. Third, the pressure equation is applied to develop the van der Waals equation of state. And fourth, the energy equation for mixtures is applied to show how mixing rules, the Scatchard-Hildebrand theory, the Van Laar theory, and the Flory-Huggins theory all result from simplifications of the van der Waals equation of state. Local composition theory is then derived from alternative approximations of the fluid structure. In this way, each constitutive relation is related back to intuitively accessible concepts that all students can appreciate, with the result that students can admire the depth of ingenuity involved in engineering models instead of being frustrated by arbitrary equations being pulled from some place known only to a privileged few.

RELATING FLUID STRUCTURE TO MACROSCOPIC PROPERTIES

To apply the relationships for relating changes in properties to C_p , C_v , p , T , V , and their derivatives, we need relationships between p , V , and T . These relationships are dictated by the equation of state. Constructing an equation of state requires considering how the intermolecular forces are affecting the energy and pressure in a fluid. As the fluid becomes dense, we know that the molecules will be closer together on the average and this will give rise to a potential energy contribution and to an increase in the contribution of attractive forces. A common practical implication of this attractive energy is the heat of vaporization of a boiling liquid.

But how can we make a quantitative connection between molecular forces and macroscopic properties? The key is to consider the average number of molecules at each distance from the center of an average molecule. To get the internal energy, multiply this average number of molecules by the amount of intermolecular energy at that distance and integrate over all distances. As for the pressure, the complete statistical mechanical derivation is beyond the scope of this introduction, but appreciation of the relevant terms can be gained by highlighting the similarity between the energy equation and the pressure equation and the relation between the potential

Students often complain that [thermodynamics] is "too esoteric." But it is also a course that can provide opportunities for giving students a strong sense of "manipulating molecules" by illustrating the development of models which address molecular scale interactions.

and the force. These considerations give rise to the energy equation and the pressure equation, and most importantly, to the definition of this "average number of molecules." The average number of molecules at a particular distance from an average molecule is given by the "radial distribution function" ("g").

The Energy Equation

$$\frac{U - U^{\text{id}}}{NkT} = \frac{\rho}{2kT} \int_0^{\infty} u g 4\pi r^2 dr \quad (1)$$

The Pressure Equation

$$Z = \frac{p}{\rho kT} = 1 - \frac{\rho}{6kT} \int_0^{\infty} r \left(\frac{\partial u}{\partial r} \right) g 4\pi r^2 dr \quad (2)$$

where

- g \equiv radial distribution function (rdf)
- Z \equiv compressibility factor
- ρ \equiv N/V is the number density
- k \equiv Boltzmann's constant
- u \equiv intermolecular potential function
- N \equiv number of atoms
- V \equiv total volume
- U^{id} \equiv internal energy of the ideal gas

AN INTUITIVE METHOD OF INTRODUCING FLUID STRUCTURE

The fluid structure described by the rdf can be initially introduced by considering two simple examples that can be solved exactly: the low density hard sphere fluid and the body centered cubic crystal. These provide the two limits of density, and the other examples can be considered as variations. The other examples are the high-density hard-sphere fluid, the low-density square-well fluid, and the high-density square-well fluid.

As a prelude to a general description of fluid structure, it may be helpful to review the structure of crystal lattices like those in body centered cubic (bcc) metals. Such lattices possess long-range order via repetitive arrangements of the unit cell in three dimensions. As an example, we can compare the structure of a body-centered cubic crystal to that of a face-centered cubic crystal. A specific arrangement of

atoms gives a single value for the density, and it correlates with many of the macroscopic properties of the material (*e.g.*, strength, ductility). Having an idea of such a specific structure for a solid provides the basis for contrast to the structure of a fluid.

The structure arising from the distribution of atoms in bcc crystals is fairly easy to understand, but how can we address the distribution of atoms in a fluid? For a fluid, the positions of the atoms around a central atom are less well-defined than in a crystal. To get started on a generally applicable description of fluid structure, think about the simplest fluid—an ideal gas.

Consider a fluid of point particles surrounding a central particle. What is the number of particles in a neighborhood surrounding the central particle? Since they are point particles, they do not influence one another. This means that the number of neighbors is proportional to the size of the neighborhood.

$$dN_V = \frac{N}{V} dV \quad (3)$$

where dN_V is the number of particles in the volume element.

Recalling that $\rho \equiv N/V$,

$$dN_V = \rho dV \quad (4)$$

If we would like to know the number of particles within some spherical neighborhood of our central particle, then

$$dV = 4\pi r^2 dr \quad (5)$$

where r is the radial distance from our central particle, and

$$N_c = \int_0^{R_0} dN_V = \int_0^{R_0} \rho 4\pi r^2 dr \quad (6)$$

where R_0 defines the size of our spherical neighborhood, and N_c is the number of particles in the neighborhood (also known as the coordination number).

Now consider the case of atoms which have a finite size. In this case the number of particles within a given neighborhood is strongly influenced by the size of the neighborhood. If the range of the neighborhood is less than two atomic radii, or one atomic diameter, then the number of particles in the neighborhood is zero (not counting the central particle). Outside the range of one atomic diameter we do not know exactly how the number of particles changes. We can express these insights mathematically, however, by introducing a "weighting factor" which is a function of the radial distance. The weighting factor takes on a value of zero for ranges less than two atomic radii, and for larger ranges we will consider its behavior undetermined as yet.

Then we may write

$$N_C = \rho \int_0^{R_0} g(r) 4\pi r^2 dr \quad g = \begin{cases} 0 & r < \sigma \\ ? & r \geq \sigma \end{cases} \quad (7)$$

where $g(r)$ is our "weighting factor" referred to as the radial distribution function (rdf). This radial distribution function provides the quantitative description of what we refer to as "fluid structure."

As a first approximation, we might assume that atoms outside the range of two atomic radii do not influence each other. Then the number of particles in a given volume element goes back to being proportional to the size of the volume element, and the rdf has a value of one for all r greater than one diameter. The approximation that atoms outside the atomic diameter do not influence each other is reasonable at low density (see Figure 1).

Far from the low density limit, we approach close-packing. The ultimate in close-packing is a crystal lattice. It is necessary to clarify what is meant by the rdf of a lattice, as opposed to its crystal structure. The rdf of a bcc lattice can be deduced from knowledge of N_c vs. neighborhood size using some elementary ge-

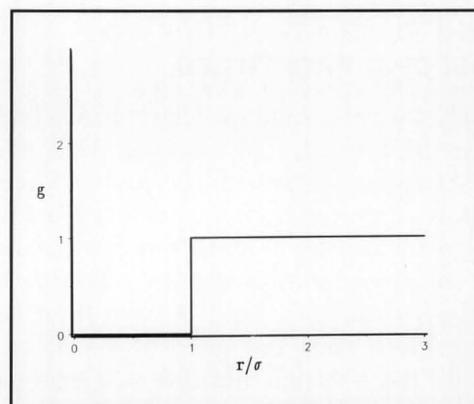


Figure 1. The radial distribution function vs. radial distance for a hard sphere fluid at low density.

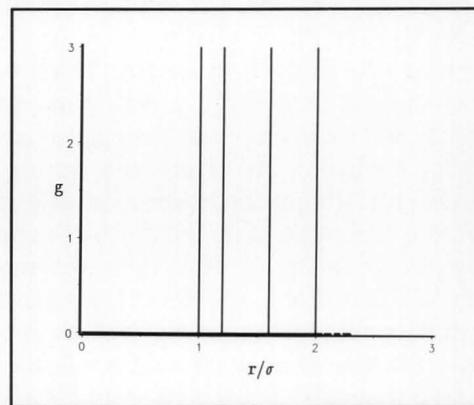


Figure 2. The radial distribution function vs. radial distance for a body centered cubic crystal.

ometry and applying Eq. 7.

If we assume that the atoms in a crystal are located in specific sites and that no atoms are out of their sites, then g must be zero everywhere except at a site. For a body centered cubic crystal, these sites are at

$$r = \{\sigma, 1.15\sigma, 1.6\sigma, \dots\}$$

For instance, the location of the second shell at 1.15σ is given directly from the length of the side of the unit cell. Since the atoms are assumed to be only at specific distances, the rdf looks like a series of spikes (see Figure 2).

The distribution of atoms in a substance is most conveniently referred to as its "structure." The structures of the low density hard sphere and the bcc crystal clarify what is meant by the rdf and how we represent it. Next, we can develop some insight about the high density hard sphere fluid. Its behavior is something of a hybrid between the low density fluid and the solid lattice. Similar to the low density case, when atoms are too far away to influence each other, the rdf approaches unity because the increase in neighbors becomes proportional to the size of the

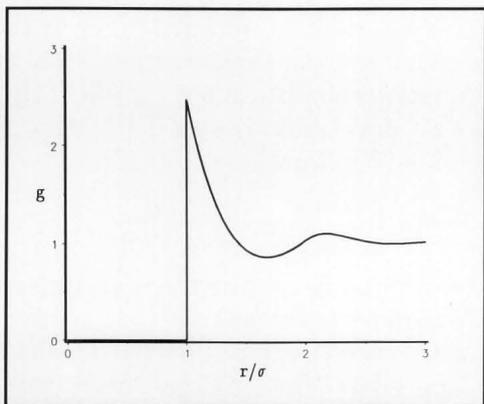
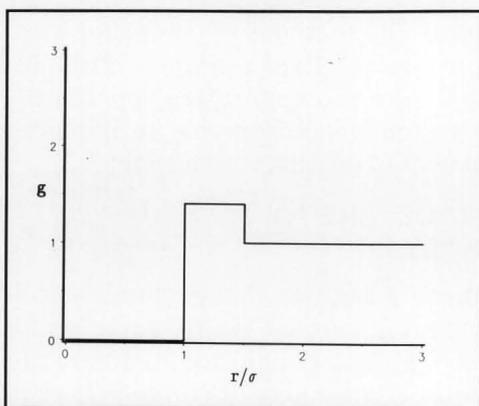
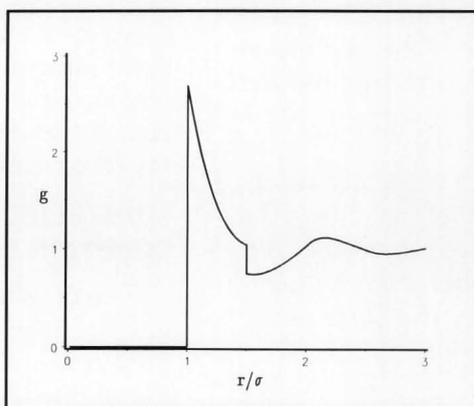


Figure 3. Radial distribution function vs. radial distance for a hard sphere fluid at high density ($N\sigma^3/V = 0.60$).



(a)



(b)

Figure 4. The radial distribution function vs. radial distance for a square-well fluid ($kT/\epsilon = 3.0$) (a) at low density, and (b) at high density ($N\sigma^3/V = 0.60$).

neighborhood. Near the atomic diameter, however, the central atom influences its neighbors to position themselves in "layers" in an effort to approach the close packing of a lattice. Thus the value of the rdf is large, very close to one atomic diameter. Because liquids lack the long-range order of crystals, the influence of the central atom on its neighbors is not as well defined as in a crystal, and we get smeared peaks and valleys instead of spikes (see Figure 3).

As a final case, consider the influence of attractive forces on surrounding neighbors. The range within the atomic diameter is still off-limits, and the value of the rdf there is still zero. But what about the rdf at low density for the range where the attractive potential is significant? We would expect some favoritism for atoms inside the attractive range since that will release energy, but overlap would still be off limits and there would be no influence outside the range of the potential at low density.

For the square-well potential, the changes with radial distance are very distinct:

$$u(r) = \begin{cases} \infty & r < \sigma \\ -\epsilon & \sigma < r < R_0 \\ 0 & R_0 < r \end{cases} \quad (8)$$

The impact of the attractive force then becomes clearly recognizable (see Figure 4a). As for the rdf at high density, we expect packing effects to dominate because attaining a high density is primarily affected by efficient packing. At intermediate densities, the rdf will be some hybrid of the high and low density limits (Figure 4b).

Qualitative description of these sample fluid structures is about as far as intuition can carry us. A mathematical formalization of these intuitive concepts is presented in several texts^[2,3] but the difficulty of such a rigorous treatment is beyond the scope of our introductory presentation. For our purposes, we would simply like to understand that something called "fluid structure" exists and that it is described in detail by the "radial distribution function."

VAN DER WAALS EQUATION OF STATE

Having laid the foundation for intuitively considering fluid structure and its impact on mac-

roscopic properties, the derivations of every theory from equations of state to local composition theory can follow in rapid sequence. These derivations can serve to illustrate model development and simultaneously demonstrate the utility of the "pure thermodynamics." One of the most successful and useful equation of state has been the van der Waals equation. Even the most popular engineering equations currently used are only minor variations on the theme originated by van der Waals. The beauty of his argument is that detailed knowledge of the rdf is not necessary—only the kind of general knowledge of its existence as described in the preceding section. As pointed out by Abbott,^[4] we can assume that van der Waals started with the pressure equation and reasoned that the integral could be broken into two parts:

$$\frac{p}{\rho kT} = 1 - \frac{\rho}{6kT} \int_0^{\sigma} r \left(\frac{\partial u}{\partial r} \right) g 4\pi r^2 dr - \frac{\rho}{6kT} \int_{\sigma}^{\infty} r \left(\frac{\partial u}{\partial r} \right) g 4\pi r^2 dr \quad (9)$$

Each integral can now be analyzed separately. Mathematically, analysis of the first integral is difficult because $g = 0$ except at $r = s$, and the derivative of the potential is zero except at $r = s$, where it becomes a Dirac delta function. This leads to the result

$$-\frac{\rho}{6kT} \int_0^{\sigma} r \left(\frac{\partial u}{\partial r} \right) g 4\pi r^2 dr = \frac{2\pi g(\sigma)}{3} \rho \sigma^3 \quad (10)$$

We have already recognized that $g(\sigma)$ increases with density, but we need a simple analytical function which can be used to provide a numerical representation of this increase. One of the simplest functions leads to

$$-\frac{\rho}{6kT} \int_0^{\sigma} r \left(\frac{\partial u}{\partial r} \right) g 4\pi r^2 dr \approx \frac{bp}{(1-b\rho)} \quad (11)$$

where $b \approx$ close-packed volume. This is the function which van der Waals suggested. It should be noted that Eq. 11 suggests that $p \rightarrow \infty$ near the close-packed density and that this helps to understand how engineering models of such divergences are often developed.

As for the second integral, this basically represents the attractive force at each distance times the number of particles at that distance integrated over all distance. As an example, consider what happens to this integral when u is given by the square-well potential (with $R_0 = 1.5\sigma$). Then

$$\frac{\rho}{6kT} \int_{\sigma}^{\infty} r \left(\frac{\partial u}{\partial r} \right) g 4\pi r^2 dr = \left(\frac{\rho \sigma^3 \epsilon}{6kT} \right) \left(\int_1^{\infty} x \left(\frac{\partial u}{\partial x} \right) g 4\pi x^2 dx \right) \quad (12)$$

where $x \equiv r/\sigma$. The integral on the right-hand side is

independent of the particular substance of interest because the only way of distinguishing different substances in the square-well potential is by different values of σ and ϵ . By factoring the σ and ϵ out of the integral, we obtain a dimensionless integral which can be applied universally to any substance multiplied by a dimensionless constant which accounts for the substance dependent values of ϵ and σ . Van der Waals did not have quantitative information available about g ; therefore he made the approximation that the value of this integral was some constant independent of T and ρ for all substances. This may seem somewhat crude since we know that g changes significantly with respect to density, but the way that g oscillates about unity leads to a weak density dependence for the integral. When this universal constant is factored in with σ^3 and ϵ , a single substance-dependent constant is obtained

$$a \equiv \frac{\sigma^3 \epsilon}{6} \int_1^{\infty} x \left(\frac{\partial u}{\partial x} / \epsilon \right) g 4\pi x^2 dx \quad (13)$$

The resulting equation of state is

$$Z = 1 + \frac{bp}{(1-b\rho)} - \frac{ap}{kT} = \frac{1}{(1-b\rho)} - \frac{ap}{kT} \quad (14)$$

When this equation is compared to currently popular equations, it is clear that the theoretical basis of modern equations of state is not significantly different from that developed by van der Waals. For example, the Soave^[5] equation is

$$Z = 1 + \frac{bp}{(1-b\rho)} - \frac{ap}{kT} \frac{\alpha}{(1+b\rho)} \quad (15)$$

where $\alpha = \alpha(T)$ is an empirically determined temperature-dependent function.

The function used to correct for the density dependence is $1/(1+b\rho)$. The principal difference is the modification of the temperature and density dependence of the attractive term, but this modification is based on experience and empiricism more than any theoretical insight. The methods of these empirical developments provide excellent examples of the interplay between theory and application, and discussion of these developments can provide keen insight into the development of engineering models.

FROM FLUID STRUCTURE TO SOLUTION THEORY

The development of solution theory closely parallels the development of van der Waals' equation for pure fluids. The final equations presented here are familiar to the reader, but the ease of relation back to the molecular perspective may be simpler than imagined at first thought. We begin with the van der Waals equation for pure fluids and consider how to

adapt it to mixtures. Essentially, all that is necessary is to define "a" and "b" for a mixture. Since "b" provides a crude representation of the close-packed volume, it is not unreasonable to crudely approximate it by a molar average. To determine the composition dependence of the "a" parameter, the energy equation can provide guidance. For mixtures, the energy equation is given by exactly the same method of adding energies times interactions that was applied for pure fluids

$$\left(\frac{U-U^{\text{id}}}{NkT}\right) = \frac{\rho}{2} \sum \sum x_i x_j \int \frac{u_{ij}}{kT} g_{ij} 4\pi r^2 dr \quad (16)$$

The only term that may seem mysterious is the factor of one-half in front. This factor arises because we imagine summing all the interactions by going from one atom to the next. But the j - i interaction is really the same as the i - j interaction, so we would be double counting if we did not divide by 2. Applying classical thermodynamics to the van der Waals equation gives

$$\left(\frac{U-U^{\text{id}}}{NkT}\right) = \frac{-ap}{kT} = \frac{-a}{vkT} \quad (17)$$

where $v = 1/\rho$ is the more traditional manner of representing the density term. Comparing Eq. (17) to Eq. (16) shows that

$$a = \frac{1}{2} \sum \sum x_i x_j \int u_{ij} g_{ij} 4\pi r^2 dr \quad (18)$$

when $x_i \rightarrow 1$,

$$a_{ii} = \frac{1}{2} \int u_{ii} g_{ii} 4\pi r^2 dr \quad (19)$$

Assuming g_{ij} is weakly dependent on composition, we obtain

$$a = \sum \sum x_i x_j a_{ij} \quad (20)$$

where the cross-term, a_{ij} , is traditionally approximated by

$$a_{ij} = \sqrt{a_i a_j} \quad (21)$$

Expressions for free energy and fugacity via the equation of state can then be quickly developed by the usual methods.

Turning our attention to Gibbs excess models for liquids, we find that we already have all of the theoretical foundation laid for many of the models. All that is required is some specific approximations and simplifications for the specific application being considered. A brief outline of the derivation of regular solution theory and Flory-Huggins theory from the van der Waals equation follows.

The Gibbs excess energy of a van der Waals mixture may be derived by considering the Gibbs departure functions of the overall mixture and the indi-

vidual components in turn

$$\frac{G-G^{\text{id}}}{NkT} = \ln\left(\frac{p(v-b)}{kT}\right) - \frac{a}{vkT} + \frac{pv}{kT} - 1 \quad (22)$$

and applying

$$G^E = (G-G^{\text{id}}) - \sum x_i (G_i^o - G_i^{\text{id}}) - \sum x_i \ln(x_i) \quad (23)$$

yields

$$\begin{aligned} \frac{G^E}{NkT} = & - \sum x_i \ln\left(\frac{v-b}{v_i-b_i}\right) \\ & - \left(\frac{a}{vkT} - \sum x_i \frac{a_i}{v_i kT}\right) + \frac{p}{kT} (v - \sum x_i v_i) \end{aligned} \quad (24)$$

A common approximation when developing solution theories for liquids is to assume that $v = \sum x_i v_{ii}$. While this is often inaccurate relative to volume estimates for non-ideal solutions, it is accurate enough for free energy estimates because the excess volume makes a small contribution to the excess free energy. This eliminates the last term in the above equation. Following Flory,^[6] we may assume that for liquids

$$v_i - b_i \sim v_i \quad (25)$$

which implies that the void fraction is roughly a universal constant for all liquids (65% is generally quite reasonable). Then,

$$\frac{v-b}{v_i-b_i} = \frac{x_i}{\Phi_i} \quad (26)$$

where

$$\Phi_i \equiv \frac{x_i v_i}{\sum x_i v_i}$$

This result is referred to as the *Flory-Huggins term*. Noting that this term is independent of temperature and applying classical thermodynamics to the free energy shows that this term describes the excess entropy of mixing and the remaining terms describe the excess internal energy. Summarizing:

$$\frac{G^E}{NkT} = \sum x_i \ln\left(\frac{\Phi_i}{x_i}\right) - \frac{U^E}{NkT} \quad (27)$$

Returning to the van der Waals theory, the internal energy may be written as

$$\left(\frac{U-U^{\text{id}}}{NkT}\right) = - \frac{\sum \sum x_i x_j a_{ij}}{kT \sum x_i v_i} \quad (28)$$

For the pure fluid, taking the limit as $x_i \rightarrow 1$, we recover

$$\left(\frac{U-U^{\text{id}}}{NkT}\right)_i \rightarrow \frac{-a_i}{v_i kT} \Rightarrow \left(\frac{U-U^{\text{id}}}{NkT}\right)_{\text{id soln}} = - \sum \frac{x_i a_{ij}}{v_i kT} \quad (29)$$

For a binary mixture, subtracting the ideal solution

result to get the excess energy gives

$$\frac{U^E}{NkT} = \frac{x_1 a_{11}}{v_1 kT} + \frac{x_2 a_{22}}{v_2 kT} - \frac{(x_1^2 a_{11} + 2x_1 x_2 a_{12} + x_2^2 a_{22})}{kT(x_1 v_1 + x_2 v_2)} \quad (30)$$

Applying $a_{12} = \sqrt{a_{11} a_{22}}$,

$$\begin{aligned} \frac{U^E}{NkT} &= \frac{x_1 x_2 v_1 v_2}{kT(x_1 v_1 + x_2 v_2)} \left(\frac{a_{11}}{v_1^2} + \frac{a_{22}}{v_2^2} - 2 \frac{\sqrt{a_{11}} \sqrt{a_{22}}}{v_1 v_2} \right) \\ &= \frac{x_1 x_2 v_1 v_2}{kT(x_1 v_1 + x_2 v_2)} \left(\frac{\sqrt{a_{11}}}{v_1} - \frac{\sqrt{a_{22}}}{v_2} \right)^2 \\ \frac{U^E}{NkT} &= \frac{(\delta_1 - \delta_2)^2}{kT} \Phi_1 \Phi_2 (x_1 v_{11} + x_2 v_{22}) \quad (31) \end{aligned}$$

where

$$\delta_i \equiv \frac{\sqrt{a_{ii}}}{v_i}$$

Substituting

$$\frac{G^E}{NkT} = \sum x_i \ln \left(\frac{\Phi_i}{x_i} \right) - \frac{(\delta_1 - \delta_2)^2}{kT} \Phi_1 \Phi_2 (x_1 v_1 + x_2 v_2) \quad (32)$$

If we choose to neglect the Flory-Huggins term, Scatchard-Hildebrand theory is obtained. The Van Laar equation may easily be derived from the Scatchard-Hildebrand form. If we choose to approximate $(\delta_1 - \delta_2)^2$ by an adjustable parameter κ , then the full Flory-Huggins theory is obtained. If we retain all of the above terms, then the theory of Blanks and Prausnitz^[7] is obtained. The development of these solution models can be interspersed with examples of retrograde condensation, azeotrope formation, distillation, and polymer mixing/blending to impress even the most skeptical application-oriented student. And the conciseness of each theoretical development makes the investment small enough to maintain interest at every step.

LOCAL COMPOSITION THEORY

There is one last class of solution theories which requires coverage even though the attention of the student has been pressed close to its limit by this stage in the course. Fortunately, the foundation for development of this theory has been laid in the form of the energy equation for mixtures and the derivation can quickly proceed as a slight modification of the previously developed solution theories. While it is difficult to motivate this further development *a priori*, it is a necessity if students are to understand the basis of the very popular and versatile UNIFAC model.^[8] The value of this investment can be reinforced by an application-oriented project which dem-

onstrates the power of the UNIFAC model.

The modification required to develop local composition theory is to realize that in developing the van der Waals mixing rules, we made a key assumption about the radial distribution function in a mixture. Briefly, we assumed that g_{ij} was independent of composition. That assumption is accurate when the components of the mixture are roughly the same size, but it becomes more questionable when their diameter ratio is greater than 1.5. Consider the differences in packing that would occur when a few very large spheres were surrounded by tiny ones *vs.* a few tiny spheres dispersed among large ones.

To develop a more accurate representation of local composition effects, we seek a description of the excess internal energy which is at least "more flexible" than that assumed by van der Waals. By more flexible, we mean to recognize that predicting complicated local composition effects may be more difficult than predicting a_{ij} . The more flexible expression we seek should be capable of at least correlating the local composition effects even if predicting them seems too difficult.

We can relate the energetics of the mixture directly to the local compositions by recalling that the intermolecular energy is a short-range function. The square-well potential is especially useful for making this point. These local compositions can then be multiplied by the energy associated with each type of interaction to obtain the total energy from the energy equation. We can define a local mole fraction by

$$\begin{aligned} x_{ij} &\equiv N_{ij} / Nc_j \\ N_{ij} &= \text{number of } i \text{ atoms around a } j \text{ atom} \\ Nc_j &= \sum_i N_{ij} \end{aligned}$$

The local mole fraction can be related to the bulk mole fraction by

$$x_{ij} = x_i \frac{N}{V} \frac{\sigma_{ij}^3}{Nc_j} \int_0^{R_{ij}} g_{ij} 4\pi r_{ij}^2 dr_{ij} \quad (33)$$

where

$$\begin{aligned} r_{ij} &= \frac{r}{\sigma_{ij}} \\ R_{ij} &= \text{"neighborhood" where intermolecular} \\ &\quad \text{energy is significant} \end{aligned}$$

Further, we can write

$$\frac{x_{ij}}{x_j} = \frac{Nc_j N_i \sigma_{ij}^3 \int g_{ij} 4\pi r_{ij}^2 dr_{ij}}{Nc_j N_j \sigma_{jj}^3 \int g_{jj} 4\pi r_{jj}^2 dr_{jj}} \equiv \frac{x_i}{x_j} \Lambda_{ij} \quad (34)$$

Noting

$$\sum_i x_{ij} = 1 = \frac{\sum x_i \Lambda_{ij} x_{ij}}{x_j} = \frac{x_{ij}}{x_j \sum x_i \Lambda_{ij}} \quad (35)$$

$$\Rightarrow \frac{x_j}{x_{ij}} = \sum x_i \Lambda_{ij} \quad (36)$$

Therefore

$$x_{ij} = \frac{x_i \Lambda_{ij}}{\sum_k x_k \Lambda_{kj}} \quad (37)$$

Substituting into the energy equation gives

$$\frac{U^E}{NkT} = \frac{1}{2kT} \sum x_j Nc_j \sum \frac{x_i \Lambda_{ij} (\epsilon_{ij} - \epsilon_{jj})}{\sum x_k \Lambda_{kj}} \quad (38)$$

In our previous development of solution theories, U^E was assumed to be independent of temperature. In local composition theory, it is more convenient to assume some temperature dependence of Λ_{ij} . In particular

$$\Lambda_{ij} = \left(\frac{v_j}{v_i} \right) \exp \left[\frac{(\epsilon_{ij} - \epsilon_{jj})}{kT} \right] \quad (39)$$

gives

$$\frac{G^E}{NkT} = \frac{C}{kT} + \sum \frac{x_j}{kT} \ln(\sum x_i \Lambda_{ij}) \quad (40)$$

where C is the temperature-independent integration constant obtained from integrating the internal energy with respect to temperature. If we set $C = 0$, we obtain the Wilson^[9] equation. If we use the Flory-Huggins theory to describe the integration constant, we obtain essentially the UNIFAC expressions. Several applications showing the predictive capability of UNIFAC can then be exemplified to reinforce the utility of having made this extension. This also provides another opportunity to illustrate the interplay between theoretical development, empiricism, and application that is so essential to engineering. Attention should be called to the number of adjustable parameters inherent in the UNIFAC model and the distinction between correlation and prediction. This also provides the necessary background for considering Sandler's^[10] award lectures without the necessity of canonical partition functions.

CONCLUSION

All of this may seem like more theory than chemical engineering sophomores can absorb. Nevertheless, we have been incorporating this material into our sophomore course for the past two years and student evaluations show surprisingly few complaints. In fact, our evaluations last year were the highest obtained over the past six years. We feel that

the key to this success is the immediate reduction of each theory to practice. Our engineering students are as pragmatic as any engineering students, but presentation of the above theoretical developments consumes only about seven lectures out of fifty-nine. The remaining lectures are devoted almost entirely to sample applications demonstrating the utility of each theory.

But there may still be some doubt on the part of thermodynamics instructors about whether this is all worthwhile. To respond, we may consider Asimov's quote given at the beginning of this paper. How close are we chemical engineers to the "manipulation of molecules on a large scale"? In reality, we teach precious little about the connections between the molecular scale and continuum scale. We occasionally hear arguments that the molecular scale and the statistical mechanics which connect it to larger scales are the domain of chemistry, not engineering. But our students do apply theories like UNIFAC. This means that they currently apply the theories blindly, like computer operators.

What we should be teaching our students is the general engineering approach to understanding a physical situation, modeling, empiricizing, and reducing to practice. Through the concept of fluid structure, we can achieve all this and maintain constant focus on the fundamental sources of energy and entropy.

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BASIC CHEMICAL ENGINEERING EXPERIMENTS

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This article is concerned with laboratory work undertaken in the early years of an undergraduate chemical engineering course and is based on the author's experiences at the University of Nottingham. Our department teaches two undergraduate courses in parallel: a six-semester BEng and an eight-semester MEng. Each semester is of fifteen weeks duration, and there are two semesters per academic year. The first four semesters are common, and it is to this portion of the course that this article is devoted.

The objectives of any student's experimental work are:

- to illustrate and reinforce chemical engineering theory and principles
- to provide hands-on experience with some commonly used process equipment
- to demonstrate experimental methodology and techniques

Further time available for laboratory work is limited.

To meet the above objectives, a wide range of experiments is required, and those used at Nottingham in the first four semesters are summarized in Table 1. The experiments must be tightly defined and carefully arranged so that a two-student team can perform the work in a three-hour session. Groups of three to six experiments are associated with appropriate modules, and in most cases students will undertake one or two experiments from this group as an integral part of the module.



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Some of the experiments listed in Table 1 are standard and are found in many undergraduate laboratories. Others are "classic" chemical engineering experiments, and yet others introduce unusual aspects to the laboratory. It is not the author's intention to describe every experiment in the table, but rather to take selected experiments and discuss

- how some of the standard experiments can be made more interesting
- how some of the "classic" experiments can be performed more effectively
- how unusual aspects can be exploited in the laboratory

LABORATORY PHILOSOPHY

The experiments are all manually controlled. This forces the students to "work the rig" and develop a feel for the way a process plant behaves. They learn that flow and pressure systems respond very quickly and hence large quantities of data can be collected very quickly, but that heat and mass transfer systems are much slower and may require considerable time to reach steady state. Some process interactions are found, *e.g.*, many students are initially surprised when steam pressure drops on increasing cold-side flow through a heat exchanger.

Nottingham's laboratory has its own boiler, and steam is distributed to most of the rigs that require heat input. This is in line with our policy of trying to emulate industrial practice and is an important element in mimicking the behavior of a "real" process plant.

Many of the experiments are designed and built with a significant glass and/or acrylic resin (perspex) content so that students can see the process operating. This is particularly important for situations such as vapor-liquid contacting, boiling, and two-phase flow. However, care is needed because poor thermal conductivity (as compared to copper or steel) can distort the heat transfer phenomena being investigated.

FLUID MECHANICS

Centrifugal Pump Operation • Since centrifugal pumps are widely used in process plants, it is important for students to become familiar with their performance characteristics. The simplest experiment, commonly performed, is measurement of head-capacity characteristics. (As an aside, it is worth considering how few student textbooks mention the head-capacity curve, let alone explain how it is used.) However, several interesting variations on the basic experiment are possible.

The first version measures head and shaft power as a function of capacity at three speeds of rotation. The speed variation is obtained by using a belt and pulley drive from a fixed-speed electric motor. Belt and pulley drives have significant friction effects, and it is important to "back out" these losses when determining the pump shaft power. To do this, the pump must be capable of being disconnected and the remainder of the system run with no load to determine a base power consumption. The shaft power is then obtained as the difference between measured power consumption of the motor in normal operation and the base power consumption.

After measuring the head and shaft power, the pump efficiency is easily calculated, and the students are able to plot the three characteristic curves of the pump: head, shaft power, and efficiency versus capacity, all with lines of constant speed. A further

feature of this experiment is that it may be used as another illustration of dimensionless correlations.^[1] In particular, the collapse of the various head-versus-capacity lines due to speed variation into one line on dimensionless coordinates is very effective.

In some large pumping operations it is necessary to run two or more pumps in parallel (e.g., cooling water circulation), and this provides an idea for another useful centrifugal pump experiment. Two pumps are run individually, in series and in parallel. Students measure the head-capacity characteristics for each configuration and learn how individual pump characteristics can be combined to predict the head-capacity characteristics for series and parallel operation.^[2] If the two pumps are dissimilar, then the limitation imposed by the lowest shut-off head of the pair again surprises students.

The third centrifugal pump experiment is simpler and demonstrates the important characteristic that a given pump will always throw up the same head at a given capacity, even though it is pumping different liquids, provided liquid viscosity is low. (This explains why water testing by a pump manufacturer is often sufficient.) Hence, as the liquids pumped have different densities, the pressure increase measured across the pump changes. Measuring the head-capacity characteristics of a pump on two different fluids (i.e., water and kerosene) is a good way to demonstrate this point.

Fluid Distribution • One of the most neglected areas of chemical engineering is fluid distribution. The operation of many real plant pieces can be impaired by mal-distribution, and the requirements to obtain approximately uniform distribution are quite restrictive.^[3,4] An experiment to illustrate the difficulties studies one branch of a pipe distributor. A variety of branches fabricated from 22-mm ID pipe, each 1.0-m long, are available. Each branch has six uniformly spaced discharge holes on the bottom, and four (also uniformly spaced) pressure tappings on the top. The branches differ in discharge-hole sizes, which range from 5.6 mm to 10.3 mm. Each branch may be connected in turn to a constant head supply of water with the throughput controlled by a throttling valve in the supply line.

When they first run the rig, most students are caught unaware by the fact that the pressure *increases* along the

TABLE 1

<p>FLUID MECHANICS</p> <p>Venturi tube*</p> <p>Pipe flow friction*</p> <p>Orifice discharge*</p> <p>Velocity profiles in a pipe</p> <p>Pressure drop in pipe fittings</p> <p>Liquid distribution</p> <p>Pump operation at varying speed</p> <p>Pumps operated in parallel and series</p> <p>Pump operated on various fluids</p> <p>Air lift pump</p> <p>MASS TRANSFER</p> <p>Measurement of gas diffusivity (stagnant film)</p> <p>Measurement of gas diffusivity (counter-diffusion)</p> <p>Wetted wall column</p> <p>Wetted disc column</p> <p>ENGINEERING THERMODYNAMICS</p> <p>Turbine isentropic efficiency</p> <p>Fan polytropic efficiency</p> <p>Refrigeration COP</p> <p>PARTICLE MECHANICS</p> <p>Packed and fluidized beds (air)</p> <p>Packed and fluidized beds (water)</p> <p>Particle elutriation</p>	<p>HEAT TRANSFER</p> <p>Heat transfer coefficient inside tubes</p> <p>Heat transfer coefficient outside tubes</p> <p>Double pipe heat exchanger</p> <p>Plate heat exchanger</p> <p>Unsteady-state tank heating</p> <p>Boiling heat transfer</p> <p>Thermosyphon reboiler</p> <p>Heat transfer in fluidized bed</p> <p>Unsteady-state heating of solids</p> <p>Temperature profiles in solids</p> <p>UNIT OPERATIONS**</p> <p>Packed column distillation</p> <p>Oldershaw column distillation</p> <p>Adiabatic humidification</p> <p>Wet solids drying</p> <p>Liquid-liquid extraction (mixer-settler)</p> <p>CHEMICAL PROCESS PRINCIPLES</p> <p>Boiler efficiency</p> <p>Mass and heat balances on internal combustion engine</p> <p>Heat balance on batch process</p> <p>Heat balance on recycle process</p> <p>*Compulsory experiment</p> <p>**Experiments take two three-hour sessions</p>
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branch and the increase is relatively more marked for the larger-size discharge holes. This phenomena is easily explained by application of Bernoulli's equation and is the cause of the mal-distribution problem. The higher pressure at the closed end of the branch causes a greater discharge rate there as compared to the inlet.

Students determine the water discharge rate from each hole and record the pressure profile along the branch for a few throttle valve settings. The procedure is then repeated for other branches, and this collected data allows the students to infer the requirements for good distribution in terms of water inlet velocity to the branch and pressure drop across the discharge holes. Friction loss along the branch is not significant in this rig. The criterion used for good distribution is that the maximum variation between highest and lowest hole discharge rates for a given throttle valve setting should be less than 10%.

Two-Phase Flow • Two-phase flow occurs frequently in process plants, and incorrect analysis or neglect may result in poor plant performance or hazardous situations.^[5] It is often an area not covered in undergraduate courses, and suitable student experiments that can be performed in three hours are rare. The easiest way to introduce a two-phase flow element into the laboratory is with an air-lift pump.^[6] The rig is based on a nominal 25-mm ID glass riser, and liquid lifts of up to 3.33 m are used. Motive air may be injected at submergences up to 5.5 m, and students are asked to investigate the variation in water throughput as the air flowrate is changed. The water throughput passes through a sharp maximum illustrating the gravity- and friction-dominated regimes at low and high air flowrates, respectively.

HEAT TRANSFER

Effect of Velocity • The fundamental experiments in this group involve measurement of inside and outside tube heat transfer coefficients. The simplest and most effective way to perform both of these measurements is to ensure that the resistance of the coefficient to be measured is the dominant effect. Hence, the inside-tube heat transfer coefficient is measured for low-pressure air flowing through a copper tube and heated by condensing steam in a surrounding jacket. Likewise, the outside-tube heat transfer coefficient is obtained by blowing low-pressure air over the "shell side" of bundles comprising copper tubes arranged on square and triangular pitches; heating is again by condensing steam, but this time it is contained in the tubes. The heat transfer resistance provided by condensing steam and copper tubing is negligible compared to the air-film

resistance, and the measured overall heat transfer coefficient is a very good approximation to the air-film coefficient. Both experiments will produce straight line plots of Nusselt number versus Reynolds number on log-log axes.

Our experience indicates that the best technique for demonstrating the effect of velocity on a liquid film heat transfer coefficient is construction of a Wilson plot.^[7] This approach is used because assuming the measured overall heat transfer coefficient approximates the individual film coefficient is not sufficiently accurate when heating a liquid. The Wilson plot takes the condensing steam, copper wall, and dirt resistances as constant, and hence the reciprocal of the measured overall coefficient can be plotted as a straight line against the reciprocal of (process water flowrate)^{0.8} if we assume that the Dittus-Boelter equation models the water film coefficient inside a tube. The experiment is performed in a steam-heated double-pipe exchanger with condensing steam in the annular space. Extrapolation of the straight line to its intercept with reciprocal of the measured overall coefficient axis gives an estimate of the sum of all the other resistances to heat transfer. Using a typical condensing steam film resistance (not very significant) and calculating the resistance due to the copper wall means the only unknown resistance, sum of the dirt films, can be determined.

The advantage of performing the heat-transfer experiments as described above is that it avoids measuring the metal-wall temperature which can be unreliable and consume considerable technician time in dismantling the equipment to investigate suspect readings.

Condensate Blanketing and Sub-Cooling • The tank-heating experiment compares warming a batch of liquid using a submerged coil in the tank with a pumparound through an external heat exchanger. The heat transfer area of the coil and exchanger are equal so for the same steam operating pressure it is interesting to observe that the tank may be heated faster or slower than by the coil, depending on the pumparound through the exchanger. Applying the equations in Perry and Green^[8] it is possible to determine the overall heat transfer coefficients for the unsteady-state heating process in each case. However, the overall heat transfer coefficient determined for the submerged coil tended to be unreproducible and lower than expected.

As originally built, the submerged coil used 6-mm diameter tubing with a large number of turns. Excessive condensate "hang up" in the coil, obscuring the heat transfer area, was suspected, and therefore

the coil was replaced by a harp using vertical tubes of 13-mm diameter tubing. The condensate now drains freely and the measured overall heat coefficient is larger, in line with the anticipated value, and reproducible.

An extreme example of obscuring the heat transfer surface by condensate was encountered in the plate heat exchanger unit. The very good heat transfer performance of the plate heat exchanger means that the steam is not only condensed but highly sub-cooled

to a temperature near that of the cold inlet process water to be heated. The plate heat exchanger is arranged for parallel flow, *i.e.*, strictly counter-current operation, but the heat transfer process deviates substantially from the commonly analyzed example in undergraduate courses. Figure 1 clearly illustrates the discontinuity in the enthalpy-versus-temperature plot which is the source of the difficulty. Analysis of the experimental results is difficult because the heat transfer areas for condensing and sub-cooling cannot be identified. The best approach is to determine $(UA)_c$ and $(UA)_{sc}$ based on an estimate of the process cross-over temperature, T' , as indicated in the figure. The performance of the unit can then be expressed in terms of the weighted temperature difference, ΔT_w , and weighted heat transfer coefficient, U_w .^[9] This experiment is important in illustrating to students that you simply do not take the four terminal temperatures of a heat exchanger to calculate a log mean temperature difference without considering the process actually occurring in the unit.

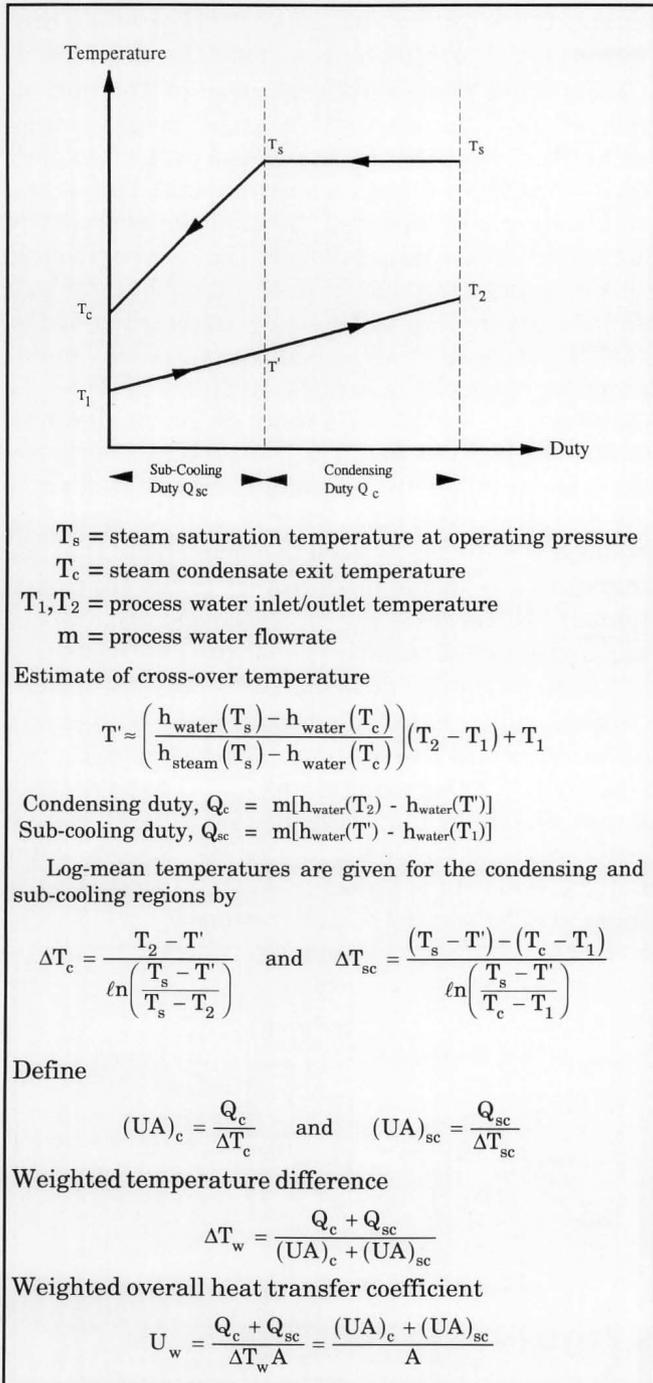


Figure 1.

Boiling Heat Transfer • One area of heat transfer where visual inspection is important is boiling. We use a proprietary rig for demonstrating nucleate and film boiling and for measuring heat flux variation with temperature difference. This works well, but industrial reboilers exhibit much more complex phenomena. The choice generally lies between vertical and horizontal thermosyphons. If a vertical thermosyphon (where boiling occurs in the tubes) is selected for laboratory work, then a heavy duty glass tube is required in order to see the boiling and the thermal resistance of the wall dominates the heat transfer. Hence, for the laboratory, boiling on the outside of copper tubes in a horizontal thermosyphon is a better choice. This construction means that condensing steam is contained in the U-tube bundle and flow boiling phenomena can be inspected through a glass shell.

The experiment most suitable for second-year students is the measurement of overall heat transfer coefficient variation with shell-side flow through the unit. But a word of caution is required—this type of unit (both laboratory- and commercial-scale) commonly exhibits an instability at low loads.^[10] In fact, an excellent third-year laboratory project is to determine the stability envelope for the unit in terms of the two parameters, steam pressure and shell-side flow.

Fluidized Bed Heat Transfer • Heat transfer from a hot surface to a fluidized bed is worth including because the heat transfer coefficient passes

through a maximum as fluidizing air flow is varied. The rig comprises a vertical copper tube (heated by condensing steam) located at the center of a small fluidized sand bed. Again, the measured overall heat transfer coefficient will be a good approximation to the film coefficient of interest. The heat transferred is based on the gain in air temperature between the bed inlet and outlet. In addition, a few thermocouples are located in the bed to demonstrate the very effective mixing which occurs and the resulting uniformity through the bed. But do not place the lowest of the bed thermocouples closer than about 25 mm to the bed support because there is a very rapid temperature transition in this region.

Ideally, students should investigate the heat transfer coefficient versus air-flow curve for various fluidized solids. Unfortunately, the rig is slow to stabilize at new conditions, and readings on only one fluidized solid are possible in the period of three hours. Correlations for heat transfer between hot surface and fluidized bed tend to be problem specific and not very accurate, so the experiment simply asks students for a comparison of the measured maximum heat transfer coefficient with that predicted by the equation of Zabrodsky, Antonishin, and Parnas.^[11]

Heat Losses • Finally, the quality of experimental results can be significantly affected by the way measured data is processed. This is particularly true of heat transfer experiments where the small scale means the rigs have a relatively high surface-to-volume ratio leading to high heat losses. This problem is compounded in some cases by the fact that rigs are left at least partially unlagged for visual inspection of the process. Good engineering practice means that students are encouraged to check the consistency of their data by comparing heat gain by the process stream with heat released from the steam condensate collected. But students need to consider which heat load to use in the calculation of heat transfer coefficients. As a rule of thumb, if a condensing steam is involved the heat losses will be large and it is best to base the calculations solely on the process heat gain. If two streams, both at modest temperature, are exchanging heat, then the average of heat gain and heat lost is likely to be the best assumption.

MASS TRANSFER

The major problem with mass transfer (and for that matter, unit operations) is that it involves composition measurement. Compared to temperature, pressure, and flow measurements, composition measurement is much more time consuming and offers a greater potential for error. Thus it is worth expending some effort to devise experiments which either

automate the composition measurement or use materials for which a simple physical measurement can be used to infer the composition.

Gas Diffusivities • The measurement of gas diffusivity in the context of a stagnant film by Stefan's method is an excellent experiment as it avoids direct composition measurement. In the case of counter-diffusion, we use Gover's method^[12] modified by introduction of a tracer gas to simplify the GLC analysis.^[13] The use of a tracer gas means that all concentrations of diffusing component can be measured relative to the tracer and thus avoids absolute concentration measurement, which is helpful.

Film Mass Transfer Coefficients • The wetted-wall column^[14] for investigating gas-film mass transfer coefficients has a reputation as a difficult experiment to make work with respect to establishing and maintaining a wetted wall. Most of the difficulty is due to the initial liquid distribution. The technical staff at Nottingham has devised a distributor which allows a stable film to be easily established at the start of a three-hour session and just as easily maintained throughout the period (see Figure 2). The only maintenance needed is cleaning of the small-diameter holes which can foul. The film produced normally has a slight ripple (as one might expect at slightly higher liquid loadings), but the data collected by students is sufficiently good to demonstrate that the Sherwood number is proportional to the (Reynolds number)^{0.8}. The rig is run on water and air, and the inlet and outlet gas compositions are easily measured by a humidity probe utilizing electrical capacitance.

To investigate liquid-film mass transfer coefficients, we use a wetted disc column^[15] and strip dissolved oxygen out of water using nitrogen.^[16] The advantage of this system is that oxygen compositions can be easily measured by using a dissolved oxygen meter and the quantity stripped is so small that the gas phase may be treated as pure nitrogen.

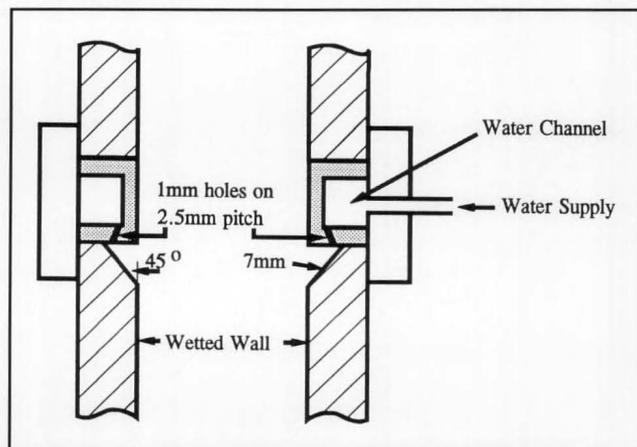


Figure 2. Distributor for wetted-wall column

UNIT OPERATIONS

Distillation • The small scale distillation columns are run on a methyl ethyl ketone-toluene mixture which has the advantage that compositions are easily inferred by refractive index measurement.^[17] The columns are run at total reflux, and the liquid from the condenser and bottom of contacting section are sampled to determine separation performance.

Students investigate the effect of reboiler heat input, *i.e.*, effectively changes vapor-liquid traffic in the column, on the separation achieved. To obtain measurable changes in distillate composition it is necessary to carefully select the composition of the mixture initially charged to the reboiler. A mixture comprising 90% toluene/10% methyl ethyl ketone is about right and will give distillate compositions in the range of 80-95% methyl ethyl ketone provided excessive separation capability is not installed (see below). Distillate compositions approaching 98%-plus of methyl ethyl ketone should be avoided.

The main problem areas of distillation experiments are heat losses and column end effects. Columns of 50-mm diameter are the very minimum to use. Despite being well insulated or vacuum jacketed, heat losses are significant, and the vapor-liquid traffic changes through the column. Thus the separation performance variation with heat input measured is at best indicative. In the case of packed columns, heat losses help accentuate the tendency for liquid channeling along the wall. Using a column

diameter of 50 mm means that a column diameter-packing size ratio of 8 can be achieved, and this helps counter channeling.

End effects are mass transfer occurring outside the contacting section of the apparatus, *e.g.*, mass transfer between liquid leaving the bottom of the contacting section and vapor rising from the reboiler. These effects can be minimized by placing the liquid sample points close to the top and bottom of the contacting section.

There is an additional end effect which is easily introduced into packed towers by using inappropriate packing support. If the vapor and liquid are not routed separately through the packing support, a liquid pool forms above the support—and the vapor must bubble through this pool. This arrangement effectively adds the equivalent of one theoretical plate to the height of packing, it distorts mass-transfer performance, and it is potentially dangerous because it induces premature flooding.

Figure 3 shows the preferred arrangement. It allows the ascending vapor to enter the packed bed through chimneys while the descending liquid drains through holes in the support plate deck. The chimneys should occupy 15-20% of the cross-sectional area, and the hats prevent liquid from draining down the inside.

The unit operations experiments require two afternoons (see Table 1). In the case of packed column distillation, two separate packed heights are investigated (one on each afternoon): 23 cm and 46 cm of 6-mm ceramic Berl saddles. If excessive end effects are avoided the students should be able to confirm that roughly twice the number of transfer units are available in the longer bed compared to the short one. The Oldershaw column distillation also takes two afternoons and investigates columns containing 3 and 5 actual plates, but the experiment provides an interesting detective challenge for the students.

The Oldershaw plates in the two columns are identical: same diameter, same number of holes, and same hole size. The three-plate column is correctly assembled and exhibits a plate efficiency of approximately 70%. But the measured separation of the five-plate column is not proportionately better, and students are asked if they can see any factors leading to the deterioration in performance.

The five-plate column is incorrectly assembled. The plates are not level, so only part of the plate bubbles and the downcomer is badly located—with the result that much of the plate is short-circuited. The experiment very effectively points out the need for proper vapor and liquid contacting.

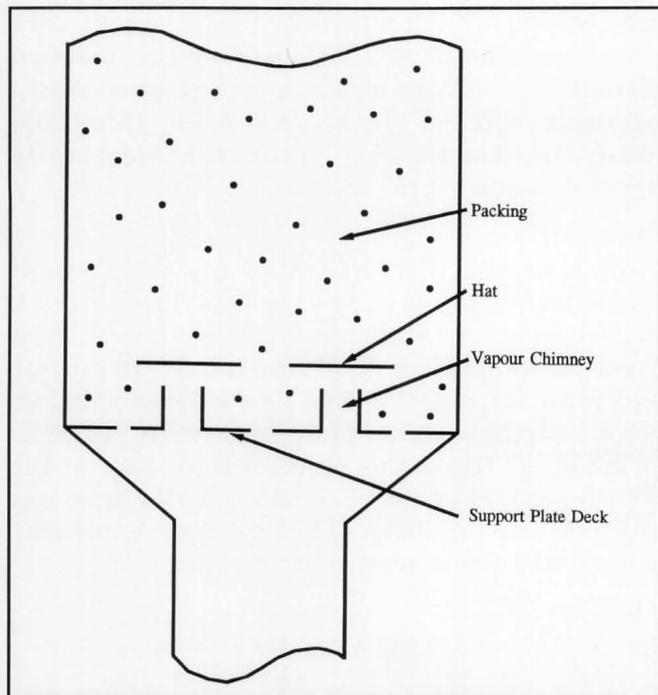


Figure 3. Packing support—simplification of a commercial injection plate.

Mass and Heat Transfer in Packed Towers • A

simple experiment illustrating the influence of gas and liquid rates on gas phase transfer coefficients in packed towers is based on adiabatic humidification^[18] using the air-water system.

Water is circulated over the packed bed in a pump-around system and it stabilizes at the adiabatic saturation temperature. Obviously, there is no liquid-phase mass or heat transfer resistance, so all the resistance lies in the gas film and the problem of interface condition has been eliminated. Compressed air (hence, of very low humidity) is pressure-reduced to just above atmospheric, and then heated to near 100°C prior to counter-current contact with the circulating water. Contacting is over a short depth of relatively open packing: 125 mm of 30-mm metal Intalox Saddles. As before, use of the air-water system means composition measurements can easily be made by using a humidity probe.

The driving force for heat transfer is the temperature difference between the air and circulating water at any elevation. Likewise, the mass-transfer driving force is the difference between the saturation humidity at the water temperature and the actual humidity of the air. If the packing depth is too great or the air flow is too low, these driving forces will go to zero at the top of the packing. It is therefore important to limit the packing depth and use high air flows in order to obtain measurable driving forces. Obtaining suitable air flows without flooding requires use of a relatively open packing, but packing wetting is then never completely satisfactory. The experimental results are particularly sensitive, as one might expect, to the condition of the humid outlet air.

The mass and heat transfer coefficients may be correlated by equations of the form^[18]

$$h_{DA} = C_D G^m L^n \quad \text{and} \quad h_{GA} = C_G G^p L^q$$

where (h_{DA}) and (h_{GA}) are the volume-based mass and heat transfer coefficients, G and L are the gas and liquid loadings on the packing, and C_D and C_G are constants. Hence, by collecting a grid of measurements comprising four gas loadings by four liquid loadings it is possible to plot on log-log axis (h_{GA}) and (h_{DA}) versus G at constant L , or L at constant G . In the time available, the values obtained for m , n , p , and q are not particularly accurate (e.g., m and p range 0.5 to 0.9, and n and q range -0.1 to 0.4), but the experiment clearly illustrates the strong dependence on G and weak dependence on L of gas-phase transfer processes in packed towers. It is also useful to illustrate adiabatic saturation temperature and as practice in heat balancing over the tower.

Liquid-Liquid Extraction • Work is currently underway on a small mixer-settler experiment for

liquid-liquid extraction. Mass transfer is from kerosene to water, with kerosene drops dispersed in water as the continuous phase. This makes it easy to recycle kerosene. (The water contains a secondary haze and should not be disposed of directly to a sewer.)

The equipment is largely fabricated from glass because wall coalescing effects are minimized when using water as the continuous phase. Further advantages are visual inspection and easy maintenance.

The experiment has a number of unusual features. One is that the component transferred is methyl red indicator which changes color from yellow to red upon transfer from the kerosene phase to water (actually 0.01-M sulphuric acid). The color intensity in either phase can be related to concentration, and hence the phases can be sampled and subjected to colorimetry to determine the concentration of methyl red. Mixer samples need to be taken through hydrophobic and hydrophilic probes. Use of kerosene-water-methyl red is based on previous experience with this system in a pilot-plant scale liquid-liquid extraction unit.^[19]

The second unusual feature is that the apparatus allows the choice of two types of settler. A vertical settler^[20,21] is used on one afternoon, and a horizontal unit^[22] is used on the second. So in addition to having the potential to investigate the effects of such variables as throughput and mixer speed on stage efficiency, students can also study the effect of throughput on coalescing band depth in the vertical settler and coalescing wedge length in the horizontal unit.

A few words of warning on the use of methyl red are necessary. The properties of kerosene can vary slightly, and so the equilibrium line for distribution of methyl red between the kerosene and water phases has to be checked occasionally. Also, commercial methyl red should be recrystallized to improve purity before dissolving it in kerosene.

SUMMARY

This article has presented an overview of Nottingham's approach to basic experimental work in the laboratory. In addition to commonly performed experimental work, a number of novel experiments and unusual approaches have been adopted that both emphasize the practices and highlight the problems of industry. The author realizes that some of the descriptions are brief and would be pleased to answer any follow-up questions or hear of other academics' experiences with similar experiments.

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REVIEW: Staged Operations

Continued from page 27.

three chapters. Chapter 7 details the tedious hand calculations performed for the design of multicomponent systems. This provides motivation for the development of a computer code to implement the methods of Lewis-Matheson and Thiele-Geddes in Chapter 8 and the shortcut methods derived by Fenske, Underwood, and Gilliland in Chapter 9.

Complex distillation methods which handle azeotropic, extractive, and two-pressure distillation are covered in Chapter 10. Chapter 11 presents a switch from continuous operation to methods associated with batch distillation using the Rayleigh equation. Chapter 12 contains information regarding staged column design including column diameter, efficiency, and tray size, while packed column design is discussed in Chapter 13. Consideration of economic trade-offs between various design options leads to a more detailed discussion of economics in Chapter 14, which addresses such topics as capital and operating costs, energy conservation, and column sequencing.

The processes of absorption and stripping are ana-

lyzed in Chapter 15, using the Kresmer equations as well as the McCabe-Thiele method. Immiscible extraction in Chapter 16 is also discussed in the context of the McCabe-Thiele analysis. For extraction involving dilute mixtures, the Kresmer equations are shown to be appropriate. Example calculations for cross-flow operations are also included.

In Chapter 17, generalizations of the McCabe-Thiele analysis are applied to washing, leaching, supercritical fluid extraction, and three-phase systems. Table 17.1 effectively summarizes the relationships between the various separation processes in terms of McCabe-Thiele analysis.

Extraction for partially miscible systems with triangular diagrams and the lever rule is analyzed in Chapter 18, and Chapter 19 introduces mass transfer concepts for design of packed beds, mass transfer coefficients, sum of resistances, and tray efficiencies leading to HTU-NTU analysis for absorbers and strippers. Note that rate-limited processes, including adsorption, chromatography, electrophoresis, and membrane separations, are included in a sequel to this text entitled *Mass Transfer Limited Separations*.

The predominant concept in this text is the McCabe-Thiele analysis. Distillation, absorption, and extraction processes are treated in terms of McCabe-Thiele diagrams. This approach emphasizes the analogies between these separation processes, which is very instructive from a pedagogical point of view. But it consequently results in a very narrowly focused book. The narrow focus is my major criticism of this text. Our current curriculum combines a study of equilibrium-staged separation processes with fundamentals of mass transfer and rate-controlled separation processes within a single course during the second semester of the third year. This text would only cover about one-third of the material for the course and therefore would require either additional texts or other supplementary material for the remaining topics. Since students are generally opposed to purchasing more than one text for any given course, I see this book filling the role of a supplementary text to complement a primary text that covers a broader range of material. The other alternative would be to devote an entire course to equilibrium-staged operations, for which this book would be an excellent text. However, with the chemical engineering curriculum already overloaded, it is difficult to justify creation of a new course for this single topic.

One additional minor criticism regards the appearance of the print. The type is not particularly easy on the eye since the book has evidently been produced in camera-ready form on a low-resolution (by printing standards) printer. □

ADVANCED ENGINEERING CALCULATORS

Don't Overlook Them!

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I recently attended a conference on engineering education where one of the sessions concerned the use of computers in the chemical engineering curriculum, during which the speakers described the use of process simulation software and spreadsheeting techniques in their teaching programs. At the end of the session I asked if they had ever given any consideration to including an instructional component regarding the use of calculators. In short, the answer was "no," and I got the impression that the matter was regarded as trivial by the majority of educators present. I also noted an inconsistency: the speakers had proudly outlined a "keyboard familiarity" component in their introductory computing program, yet with regard to calculators they voiced the opinion that "one should not have to teach the students absolutely everything—some things they should learn by themselves!"

I agree wholeheartedly with the latter belief. Indeed, it is fundamental to the university teaching concept that students must take the major responsibility for their own learning. I also applaud the inclusion of computing skills in the curriculum; the proliferation of affordable and powerful personal computers over the past decade and the emergence of spreadsheets as an engineering tool combine to make this essential for the engineering graduate.

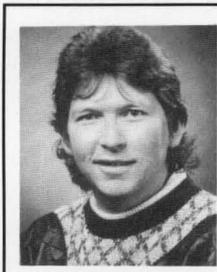
But I take issue with the commonly held belief that calculators are only a trivial component of the myriad

of tools available to the professional engineer. How many of today's engineering educators would be surprised to learn that the calculator that I currently hold in my hand is capable of storing more than one megabyte of information, available as RAM, and ten megabytes of numeric information using data compression? By way of comparison, this magnitude of memory has only recently become widely available for personal computers.

The amount of available memory is only one aspect of today's advanced calculators; the real power of these tools lies in how the information is utilized, and I submit that it is this aspect that should be treated seriously in the engineering curriculum. In the following discussion I will lean heavily on my personal experience with one advanced calculator; the Hewlett-Packard HP48SX Scientific Expandable. It is not intended to be an endorsement of this particular product or brand—in my opinion other makes of calculators will likely soon rival the HP48SX, if they do not do so already.

COMPUTERS EMBRACED— CALCULATORS IGNORED

Before elaborating on the calculator's capabilities, I want to give my view of how today's attitudes towards computers and calculators developed. I believe the main reasons for the different attitudes are 1) that, unlike the PC, the advanced calculator does not occupy a position of usefulness in the general populace, and 2) that these two tools were introduced at opposite ends of the utility spectrum. The PC was driven by commercial (industrial) implementation and was viewed as a way of putting mainframe computing power in the hands of a single user. Huge efforts in software development and the advent of user-friendly software interfaces, pioneered by Apple's Macintosh, have made the personal computer an invaluable tool. This was quickly recognized by the educational sector and accordingly was incorporated into the curricula. Teaching efforts were at first directed toward the development of programming skills but, arguably, the evolution of spreadsheets and other



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user-friendly packages have made this aspect (for chemical engineers at least) less important in recent years. The personal computer has been embraced by educators.

In contrast, the calculator (at least in its affordable form) had its origin at the very lowest level of the utility scale, and it has never enjoyed the commercial development to the extent that the personal computer has. Whereas personal computers can be used across a whole range of disciplines, from musical composition to nuclear physics, the advanced calculator requires some measure of mathematical sophistication of its user. This dramatically limits its market.

At first, the calculator offered only the four basic mathematical functions, replacing the slide rule. It was seen by the old guard as not only unnecessary but also as an actual threat to the development of "essential" basic mathematical skills. To a certain extent those fears have been realized—we of the latest generation of engineers are probably neither as quick at "in-the-head" calculations nor as good at estimating magnitudes as our predecessors were. (The argument could be made that these skills are not as necessary as they once were. Perhaps the necessity of "in-the-head" calculational skills for an engineering professional is itself a subject for debate.)

The calculator evolved to incorporate trigonometric and hyperbolic functions and, eventually, also elementary statistical functions. Programmable calculators appeared, but they were limited by available memory to low-level languages and a finite number of steps. Although various software applications became available, the initial programming capability was basic and time-consuming. For the student, the usefulness of programming came mainly from the automation of short, but tedious, repetitious number-crunching during laboratory classes.

Alphanumeric displays soon followed, and the student was now presented with higher-level languages, the ability to write user-friendly software, and the capability of storing information. With the advent of larger displays came the ability to quickly and easily plot functions and experimental data. Today, built-in functions allow an engineer to enter eight or ten data points and perform a regression analysis on the spot, within a few minutes, without programming.

The following anecdote highlights the inaccessibility of advanced calculators to the public at large (and even to other professional groups), which contrasts distinctly to the accessibility (and hence the popularity) of personal computers. A consulting engineer was giving expert court evidence for the defense and was
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asked by the prosecution to estimate the outcome of an hypothetical situation. The engineer replied that he could not give an immediate answer since he did not have his calculator with him. Smelling blood, the prosecuting attorney offered the use of his own calculator, which had the four basic mathematical functions. The engineer reiterated his inability to give an immediate answer without his own calculator, at

Rather than viewing this as just another subject vying for attention . . . , perhaps it should be looked at as a way of easing the teaching load, alleviating the drag caused by those students who are overloaded with mathematical tasks of dubious educational value.

which the prosecutor, this time smelling victory, cried, "And you call yourself an expert?" This naive attempt to question the engineer's competence backfired when it became evident that the calculation required a more sophisticated calculator and that the prosecutor obviously did not understand the point of his own question. The lesson is clear: the calculator has evolved from its basic form into a device that requires considerable mathematical sophistication to simply comprehend its potential utility.

For this reason it is only the knowledgeable users who have driven its evolution and incorporated it into everyday use. At each stage of its advancement students have recognized the potential advantages of the calculator's latest implementation (some cynics might say it is only a result of the student's general tendency to find the easiest route through any course), whereas educators have consistently lagged behind and have blocked its use by banning them from exams. In all cases, the bans have eventually been relaxed, but the negative knee-jerk reaction to new technology persists at each stage.

CAPABILITIES OF THE LATEST CALCULATORS

I agree with the conference speakers that up until the above stage of development, students could learn to use calculators to their full capacity by themselves. After all, these devices merely offered quick number-crunching. Once you knew where the "cosine" button was, what more was there to learn? But the current generation of calculators has surpassed mere number-crunching and in the process has outstripped the student's ability to comprehend their potential uses, let alone to readily assimilate the available functions. My own calculator comes with an 852-page manual, plus an additional 230 pages for one of the expansion cards, not to mention the 290-page external

programmer's development manual.

To illustrate my points further, let me describe my calculator. (Once again, I advise that the following is not intended to be an endorsement of a particular product, and it obviously doesn't even approach an objective, critical analysis of functionality!)

I have owned an HP48SX for about eighteen months now and still have not grasped its entire functionality. (I had previously owned two earlier models of the same make.) The calculator has a 131x64 pixel graphics display (which acts as a window onto a much larger display area), divided into seven lines for text. It has forty function keys, each having four built-in functions and up to six user-defined functions, giving 400 immediate-entry functions. In addition, there are six "softkeys" which take on various functions according to the particular mode the calculator is in. For instance, in the "Statistics" mode, these six keys have 35 functions (plus user-defined functions) displayed on-screen in hierarchical sets of up to six functions at a time. In all, the calculator has 2100 built-in functions.

It has, built in, 32k of ROM and 32k of RAM, with two expansion slots for plug-in 32k, 128k, or 512k cards that can be operated as ROM or RAM. In addition, the calculator uses kermit protocol to communicate with remote devices (*e.g.*, a personal computer) via an RS232 port and features an infra-red communication port for transferring data to a printer or to another calculator. The power of the above features alone is considerable. I also have eight megabytes of application software for the calculator, stored on my PC, which I can download or upload at any time.

Do you still think the calculator is a trivial tool? Read on . . .

The calculator is capable of symbolic algebraic manipulation, differential and integral calculus, so I can enter a function in algebraic mode (without programming) and isolate a variable, simplify the expression, differentiate any variable (and define others as functions of one or more variables), and integrate between limits. It can even handle differential equations. With the calculator, I can perform vector and matrix algebra and solve systems of linear equations. Application software offers Gaussian elimination, row reduction, and determination of eigenvectors and eigenvalues. Think of the advantage, for the student learning process control, offered by a calculator that can perform Laplace transformations, solve partial fractions, and produce Bode plots. This one can do all of that.

The calculator has 147 built-in units which can be combined in any consistent way and allows user-defined units to be stored. It not only converts between units, but also allows the user to attach units to any value and perform mathematical manipulations, keeping track of unit consistency. For example, I can add 10 ft/s to 10 mph and get 25 ft/s. (10 ft/s + 10 psi rightly gives an error.)

One of the most powerful features is the built-in equation-solver. With this I can enter an equation algebraically (no programming necessary), and the calculator automatically gives an on-screen menu of all variables involved and allows me to enter known variables (with or without units) and solves for the unknown. I can then change any values and re-solve. This provides a "what-if" platform with obvious value in design problems. Another available application is the multiple-equation-solver. It links equations together and solves for any unknowns. For example, in the plug-in Equations Library Card, one application has eight linked equations for fluid flow. They are

$$\rho \left(\frac{\pi D^2}{4} \right) v_{avg} \left(\frac{\Delta p}{\rho} + g \Delta y + v_{avg}^2 \left(2f \left(\frac{L}{D} \right) + \frac{\sum k}{2} \right) \right) = w \quad (1)$$

$$\Delta p = p_2 - p_1 \quad (2)$$

$$\Delta y = y_2 - y_1 \quad (3)$$

$$M = \rho Q \quad (4)$$

$$Q = A v_{avg} \quad (5)$$

$$A = \frac{\pi D^2}{4} \quad (6)$$

$$Re = \frac{D v_{avg} \rho}{\mu} \quad (7)$$

$$n = \frac{\mu}{\rho} \quad (8)$$

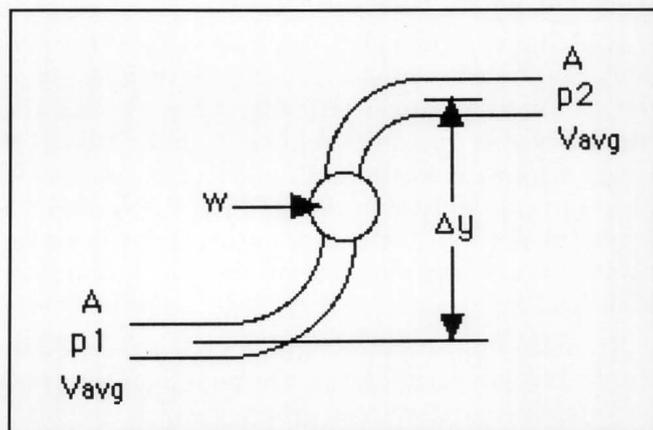


Figure 1. Equations Library Card display of fluid-flow system

(Nomenclature is standard and not worth including for the purposes of this discussion.)

The press of a softkey displays each of these equations in turn, and another softkey displays an on-screen picture of the system as shown in Figure 1. Another softkey yields a description of the variables and even the default units (the user may choose SI or English):

Δp	pressure change, kPa
p_1	initial pressure, kPa
p_2	final pressure, kPa
Δy	height change, m
	etc.

By plugging the known values into the given menu of all variables, the multiple-equation-solver can then be asked to search through all eight equations and solve for any unknown variables, repeating the process until all possible solutions for unknowns have been obtained from the given information. For identification purposes, calculated values are tagged differently from specified values.

The Equations Library Card has 128k ROM and includes 315 common equations, organized under fifteen categories (Columns and Beams, Fluids, Electricity, Solid Geometry, etc.). Also included are a financial calculation package with time-value-of-money, a set of engineering utilities (Re, friction factor, etc.), and a collection of 39 commonly used physical constants (gas constant, Boltzmann's constant, etc.). Finally, it includes a periodic table of the elements which contains all the chemical data that appear in a standard periodic table of the elements. The primary user-interface is the familiar grid of elements and the user can select any element and obtain a catalogue of 23 properties (melting point, conductivity, etc.), each of which may be plotted against atomic number. A molecular weight calculator allows typing in of formulae and quick calculation of atomic weights.

Still a trivial and readily assimilable tool?

I have made no mention of the calculator's abilities regarding complex numbers, binary arithmetic, or user-defined functions, and have barely touched on algebra, calculus, statistics, arrays, interactive plotting, etc. Finally, a high-level language is available to the user and an even more comprehensive instruction set (plus machine code) is available on the freeware set of PC development tools for creating and downloading application software for the calculator.

THE PRESENT AND THE FUTURE

The point of the above description is to show that calculators have now advanced far beyond the complexity and capacity at which computers were welcomed into the engineering curriculum. The abilities of today's advanced calculators go far beyond the immediate capabilities of most (particularly the less-advanced) undergraduates, yet their education could be enhanced considerably by incorporating instruction on the use of the latest tools into the curriculum. It is not sufficient to allow students to flounder about, applying tools beyond their level of comprehension and obtaining competence only (if at all) in piecemeal fashion.

For those readers whose first instinct is to identify and ban the most advanced calculators, I urge you to think again. Recent history shows that such bans do not last and instead a redesign of the things we are testing is required. Indeed, if the advanced calculators are such a threat during exams, then their value as tools is self-evident! But many educators tend to ignore them during the student learning process and attempt to abolish them during the student evaluation process. This is a surprising oversight for supposedly liberal institutions of higher education. Are we doing justice to the teaching process if we ignore these tools at the very time that an emerging professional requires the most guidance?

Our students use, and will continue to use, increasingly sophisticated calculators on their own throughout their university years and certainly beyond them. The knowledge-base of students has steadily risen from year to year (the derivation of Schrodinger's equation is standard first- or second-year chemistry and superconductors are now old-hat). We must allow more and more sophisticated tasks to be delegated to number-crunching tools in order to make room for the new knowledge. Should our students really be spending their time struggling through eigenvector and eigenvalue calculations when they could instead be studying the relevant application in more depth? (This is not to say, however, that students needn't thoroughly understand the concepts of eigenvectors and eigenvalues.)

Are those of us in the educational sector of the engineering profession ignoring an opportunity to contribute to the direction of the calculators' continued development? After all, they *will* continue to develop, with us or without us. With the substantial increases in solid-state memory capacity which are certain to come, perhaps we will see the advanced calculator being aimed at specific disciplines. That is, instead of being aimed merely at business or engi-

neering professionals in general, as they are at present, we may see calculators aimed specifically at chemical engineers. Such a series of calculators might consist of a common hardware core, with large-capacity plug-in modules of extremely specific information and operations which customize the calculator for particular professions.

My own view is that the computing component of the engineering curriculum should include serious treatment of advanced calculators and that their use in all aspects of engineering education (including student performance evaluations) should be encouraged. I do not suggest offering a course specifically on calculator usage for two main reasons. First, how could one justify the selection of one brand over another, or indeed the selection of calculators *per se* over, for instance, spreadsheets as a topic worthy of instruction? Second, the utility of such material would rely heavily on existing technology which quickly becomes outdated, leaving the graduate no further ahead.

Rather than viewing this as just another subject vying for attention in an already overcrowded curriculum, perhaps it should be looked at as a way of legitimately easing the teaching load, alleviating the drag caused by those students who are currently overloaded with mathematical tasks of dubious educational value. In particular, using advanced calculators could give the instructor an opportunity to place greater emphasis on "what if"-type problems from which the students can quickly grasp the effect of varying the parameter values on the outcome of a solution without significantly increasing the time required for completing the assignment.

Certainly, the future of calculators is aimed at more comprehensive and sophisticated utility for the engineering professional. We should take them seriously. □

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Continued from page 41

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Review: Process Dynamics

Continued from page 33.

has costs and benefits. The most evident cost is that a sequential reading gives a repetitious treatment of some topics. Material regarding PID implementation is found in at least three different parts of the book. Stability is treated in different parts with distinctly different approaches. Counting the degrees of freedom in a process is discussed in both the first and last parts of the book. A more subtle penalty is that this already large book doesn't have room for more detail on some important topics. Anti-reset windup, for example, is mentioned in passing. Thus, an instructor has to carefully plan an approach to the book and what parts to emphasize or omit. Students also have to be patient with the discursive nature of the book.

Of course, the positive side of modularity is that the book can be adapted to a variety of uses. This is a strong feature, given that process control courses are often by academics who are not experts in the field. This is enhanced by the large set of well-chosen, end-of-chapter problems.

References to widely available tools for computer-aided control analysis are given in a separate appendix. Unfortunately, these are not incorporated into the text or problems. Matlab and its associated toolboxes have been widely adopted in many universities. A low-cost student edition of Matlab is now available which would be a good supplementary text for a course based on this book.

Process control is a rapidly growing subject driven by advances in computing technology, needs for improved process automation, and new theory. This text gives a contemporary overview in an accessible, teachable format. I suspect that the ideal turn-of-the-century course will deemphasize complex variables in favor of statistics, optimization, and model predictive control. But in the meantime, this book is a worthy competitor for market dominance among existing process control textbooks. □

Chemical Engineering Education

AUTHOR GUIDELINES

This guide is offered to aid authors in preparing manuscripts for Chemical Engineering Education (CEE), a quarterly journal published by the Chemical Engineering Division of the American Society for Engineering Education (ASEE).

CEE publishes papers in the broad field of chemical engineering education. Papers generally describe a course, a laboratory, a ChE department, a ChE educator, a ChE curriculum, research program, machine computation, special instructional programs, or give views and opinions on various topics of interest to the profession.

• Specific suggestions on preparing papers •

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