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chemical engineering education

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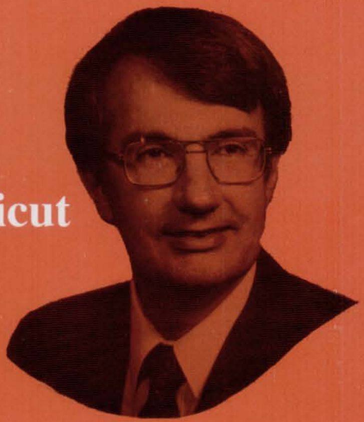
# *Michael B. Cutlip*

*of the*

**University of Connecticut**



*feature article*

**Seven Rules for Teaching**
*R. Byron Bird*

*and . . .*



*also . . .*

# M.I.T.'s

*School of Chemical Engineering Practice*

Chemical Engineering Division of American Society for Engineering Education

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# M. I. T.'s SCHOOL OF CHEMICAL ENGINEERING PRACTICE

## *The Powerful Potential of Alumni Support*

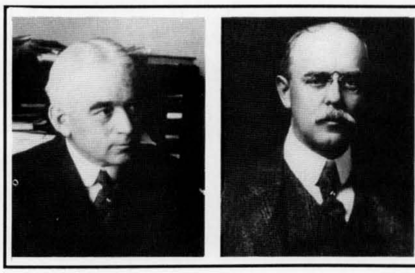
### *...or....How Its Graduates Matched Their Enthusiasm with Their Money*

JOHN I. MATTILL
*Massachusetts Institute of Technology*
*Cambridge, MA 02139*

*In January of 1980, Selim Senkan and J. Edward Vivian wrote an up-beat description of MIT's School of Chemical Engineering Practice (SCEP) for this journal.[1] What they did not emphasize in that paper was that this unique educational program, then in its 64th year, had some threatening liabilities as well as the assets they so ably celebrated. When some of those liabilities materialized in the next decade, graduates of the Practice School, many of them among the top leadership of the U.S. chemical industry, moved aggressively to support this unique concept in chemical engineering education. Indeed, the School today is an example of the influence that alumni can have on professional education in chemical engineering.*

*To tell this story is, in fact, to tell a brief history of the School. What follows is a radical condensation of the history prepared by the author as a complement to SCEP's 75th anniversary celebration in 1991.[2]*

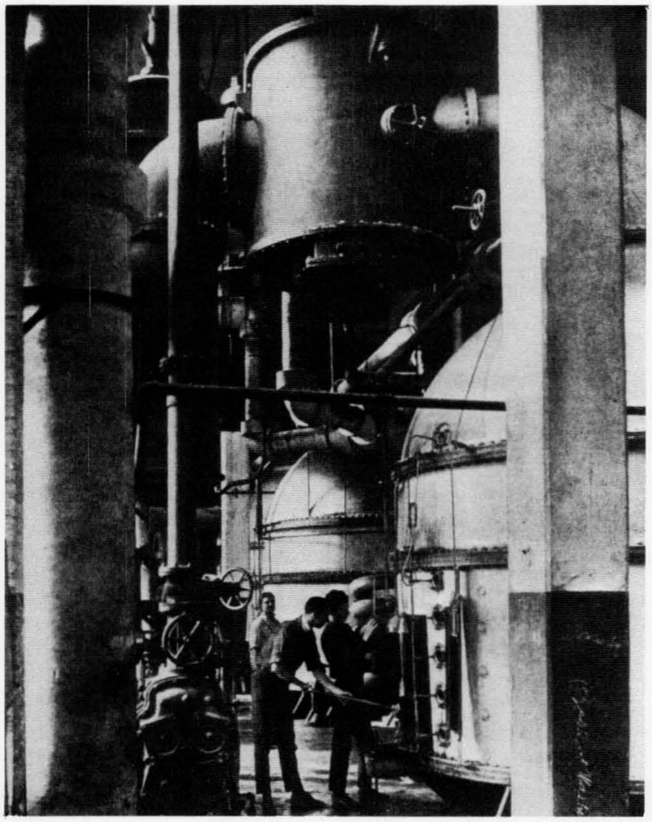
From the beginning of instruction at the Massachusetts Institute of Technology in 1865, there was an option in "practical and industrial chemistry," and by 1888 it had become the nation's first four-year curriculum in chemical engineering. Beginning in 1884, its head was William H. Walker, an entrepreneurial analytical chemist trained at Penn State and the University of Gottingen. One of Walker's major concerns in teaching chemical engineering was to help students understand how chemistry was different when scaled up to industrial dimensions. For many years, he gave his students a sense of the industrial environment by taking them on week-long tours of major chemical plants in the Northeast. But by 1914 enrollment had become so large that the difficult logistics of such tours proved insoluble, and they were terminated.



*The School of Chemical Engineering Practice was conceived jointly in 1915 by William Walker (L) and Arthur D. Little (R), whose own career proved that even young people without chemical degrees could contribute significantly to the chemical industry.*

*Photographs courtesy M.I.T. Museum*

Walker, however, remained concerned about how to best introduce his students to chemistry in industry. His friendship with Arthur D. Little, who had entered M.I.T. in 1881 to study industrial chemistry, was to eventually lead him to the solution to that problem. Little never finished the four-year curriculum—financial needs and his impatience with academics led him to go to work in 1884 as assistant chemist in



Photograph courtesy M.I.T. Museum

*In the early years, the Practice School was concerned as much with teaching the scale as the sophistication of industrial chemistry. These students in the School's first post-World-War-I class were photographed at the Revere Sugar Refinery near Boston.*

a small paper mill in Rhode Island where, despite his modest academic credentials, he almost single-handedly perfected the plant's sulphite papermaking. Soon thereafter, Little became a pioneering and successful consultant, and he presently was chosen for membership on M.I.T.'s Corporation—its board of trustees.

As Little's success demonstrated, the country's fast-growing chemical industries were desperate for technical help—just as Walker was desperate to give his students industrial experience. The logic was inescapable, and Little and Walker devised an elegantly simple exercise of it. M.I.T. would establish branches (they were called "stations") at several chemical plants. Faculty would be augmented so that two teachers could be in residence at each station, and groups of Master's students would visit the stations to learn plant operations under supervision of the resident faculty. In between terms and during summers the resident faculty would work on technical problems for the host companies; they would likely be the companies' most sophisticated research and development people, and if they needed even more expertise, it could be obtained from M.I.T. colleagues. The companies would meet the stations' operating costs, and M.I.T. would pay the faculty salaries.

***As Little's success demonstrated, the country's fast-growing chemical industries were desperate for technical help—just as Walker was desperate to give his students industrial experience. The logic was inescapable, and Little and Walker devised an elegantly simple exercise of it.***

Little solicited a $300,000 gift (a prodigious sum in 1916 dollars) from George Eastman to build the needed stations. As it turned out, the companies in their enthusiasm built the needed stations themselves (offices, libraries, adjacent small laboratories), and Eastman's gift became a useful nest-egg for the Practice School. The scheme quickly drew the approval of M.I.T.'s faculty, administration, and Corporation, and a communication to the *London Times Engineering Supplement* applauded the experiment for chemical engineering students "who have no doubt found that dexterity with flask and test tube does not create precisely the self-confidence needed by the chemist who is working with, say, 25,000 gallons of acid in a digester."[3]

During their six weeks at each station, the students' assignments included creating and drafting a plant flow sheet, laboratory exercises using the plant's test equipment, lectures by the faculty and selected company staff followed by a series of "home quizzes," and group work on several plant problems that typically involved measuring the effects of changes in one or more process parameters. Each student served at least once as a project leader for a group of three to five colleagues, and each group was required to make formal presentations of project plans and progress reports in addition to verbal and written final reports. Students often had to devise and build the test equipment they needed, and every student worked on at least one problem that required taking data for a 16-to-24-hour period. Alumni complain that there was never enough time to do everything. But the faculty were unresponsive; they wanted the program to replicate the characteristics of professional work—the pressure for results, the need to innovate technical methods, and the problems of group leadership, project planning, and technical reporting. Alumni almost without exception suggest that this mission was accomplished;

the School gave students confidence and a powerful enthusiasm for the profession they were entering.

Some interesting comments by students in the Practice School's first class in 1917 are:

- *Every member of the group is impressed with the change from the theoretical viewpoint of the classroom to the practical viewpoint of the course.*
- *To say a Guy-Lussac tower is so many feet high is one thing but to climb it is another.*
- *We are gaining an interest in our work that has never been equalled, and we are gaining a friendship with men of importance in our profession.*

As late as 1949, Gerald Lessells, now retired, was having experiences that were typical of SCEP's earliest years: "We had been working since eight the previous morning, getting ready for a stream-flow measurement in a high-pressure steam line. After machining our own orifice and setting up for pressure-drop measurements, we stood aghast in the small hours of the next morning as our sole achievement was to blow the mercury in the manometer into the steam line. We quit, almost in tears. But we finished successfully the following day. That was forty-one years ago, and I still can remember the frustration, and later the sense of fulfillment, when we reached our goal."

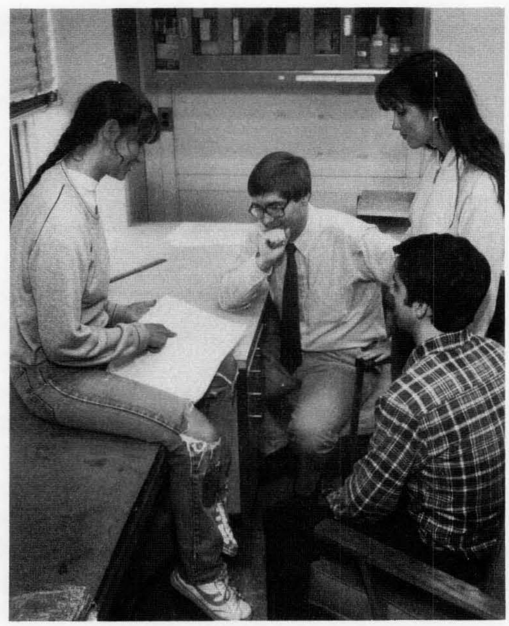
Since then there have been evolutionary changes. Today, the Practice School programs focus almost entirely on problems suggested to the resident faculty by company technical personnel who then become the students' consultants on the projects. Students' reporting sessions are, in effect, plant seminars attended by both company personnel and M.I.T. representatives; Practice School alumni are especially enthusiastic about their experiences in preparing and presenting reports, the final versions of which ended up in the host companies' proprietary files. Practice School faculty have no roles in companies' research except to help identify technical problems suitable for student projects and to help

Photograph courtesy Oak Ridge National Laboratory, from M.I.T. Museum

*Reporting project results to colleagues and company hosts is cited by alumni as an important contribution of the Practice School. Shown above is Elsa Kam-Lum, the second woman to attend the Practice School, at the Oak Ridge Station, 1973.*

students fulfill the companies' needs.

The students, whose role is likened to that of outside consultants, are unpaid—which gives them license to continue the traditional complaints about intense pressure and overload. But they continue to draw confidence from their work (which typically becomes company property) and to take great pride in it. Projects of Practice School students at American Cyanamid's Bound Brook plant between 1962 and 1967 were said to have saved that company an average of $160,000 a year, and savings of millions of dollars are attributed to two student projects at Dow Chemical Company in the 1980s.



Photograph courtesy Bethlehem Steel Corp., from M.I.T. Museum

*A typical student-faculty ratio and relationship: Professor George Huff ('82) with three students at the Bethlehem Station (1982-1984).*

In the 1960s, as the Practice School passed its 50th birthday, however, a host of problems began to press on it:

- This was a time of growing emphasis on "engineering science," especially at M.I.T. Practical experience such as emphasized by the Practice School was out of style, and many students (and some staff as well) thought SCEP was irrelevant. Enrollment fell.

- In order to attract students, M.I.T. asked the host companies for help with the students' expenses at the stations, and companies subsequently agreed to provide funds that could be awarded as fellowships to cover tuition and a part of living expenses. But tuition was rising faster than the rate of inflation, and companies found these rising commitments onerous.
- Despite these stipends for their semester at the stations, students found the Practice School an expensive option. Away from the campus for one semester, they were poor candidates for on-campus research or teaching assistantships that were available to most other graduate students.
- The Practice School was clearly a cost center for M.I.T. as well as for its host companies. With two members of the faculty at each station, Practice School students enjoyed the Institute's lowest student-faculty ratio, and higher housing costs resulted from the arrival of women and married students. The Eastman funds were long gone.
- More and more foreign students came to M.I.T., and far more in proportion than American students sought out the Practice School as a way to learn about American industrial practice. But to the companies foreign students were vexatious—unlikely to be available for employment after graduation and very likely to carry American methods back home to overseas competitors.

*Photograph courtesy Esso, from M.I.T. Museum*

*Professor Warren K. Lewis ('05), who taught at M.I.T. from 1908 until well beyond his official retirement in 1948, regularly visited the stations—shown here at the Bayway Station in 1959.*

For all these reasons, by the late 1970s SCEP began to look to the M.I.T. administration more like a liability than an asset, and its termination seemed likely.

But its alumni had not yet been heard from, and almost from the year of its founding the Practice School was distinguished by the enthusiasm of its former students—an esprit probably greater than among the alumni of any other graduate-level program at M.I.T. Fully ninety percent of the funding for the department's new building in Cambridge, dedicated in 1976, had come from Practice School alumni or companies that they founded. When queried in 1991 (in anticipation of the School's 75th anniversary), an extraordinary number of them wrote enthusiastic recollections, saying that their Practice School experiences had been pivotal in shaping their careers.

Peter Melnick ('52, Hercules, Inc.) credited SCEP with "a hands-on practical experience that opened up the real world of industrial manufacture, revealing how everything in engineering is tied together." Ralph Landau ('41) said, "I never worked so hard in my life, but I really learned how to concentrate and get a job done under forced draft." Vernon Bowles ('33) remembers the Practice School as "the greatest experience of my educational encounters."

Because they were prominent in the profession, SCEP alumni were prominent in the councils of M.I.T.—including especially the Corporation's Visiting Committee to the Department of Chemical Engineering. Unmoved by an estimate that $180,000 a year might be needed to overcome the problems that beset the School, they stonewalled any suggestion of terminating what Professors Senkan and Vivian had called "a continuing catalyst in engineering effectiveness."[4]

One of the trump cards was played by Charles Reed ('37), whose doctorate in chemical engineering from M.I.T. had not included SCEP experience. In 1977, as General Electric's senior vice president for corporate technology, he had invited SCEP to open a station at GE's chemical plants in Waterford and Selkirk, New York; he thus rescued the Practice School from the embarrassment of a two-year search to replace its station at Bound Brook, New Jersey, terminated when American Cyanamid found the escalating costs too high. Upon hearing the project reports by the first class at the Schenectady station, Reed wrote M.I.T. that the students "did an extraordinarily good job of presenting (their) results and recommendations. I was really delighted." Returning to his office from Schenectady after a similar session the

***The decisive event was the commitment by John Haas ('42), then vice-chairman of Rohm and Haas, to head a fund-raising effort among companies in which SCEP alumni held major posts. Haas had come to M.I.T. from a liberal arts background, and he says "I didn't know what a reactor was until I went to the Practice School."***

next year, Reed reported to M.I.T. President Jerome B. Wiesner, "I was tremendously impressed with the great range and high quality of the projects being worked on . . . . (The students') studies have resulted in recommendations expected to (yield) savings of $400,000 to $700,000 a year . . . . (The Practice School provides) a most important type of experience that many of us wish we could have had at an early age. In my opinion, this is really unusual and highly valuable graduate education."

The decisive event was the commitment by John Haas ('42), then vice-chairman of Rohm and Haas, to head a fund-raising effort among companies in which SCEP alumni held major posts. Haas had come to M.I.T. from a liberal arts background, and he says "I didn't know what a reactor was until I went to the Practice School." He, Landau, and twelve other prominent alumni, establishing themselves as "Friends of the Practice School," in 1980 completed a $600,000 fund for fellowships for Practice School students while in Cambridge. Donor companies received only one "perk" as an incentive—they had first review of the resumes of all M.I.T. chemical engineering graduate students about to receive their degrees.

But the Friends' fund was a wasting grant that would soon enough be exhausted and plunge SCEP back into uncertainty. So in 1981, Haas made a new proposal. The Phoebe Hass Charitable Trust, he said, was considering a $500,000 grant to M.I.T. If he persuaded his M.I.T. undergraduate classmates to match that gift for their 40th M.I.T. reunion, would the Institute commit the resulting $1 million Class of 1942 Professorship to a member of the faculty who would have the goal of stabilizing SCEP operations within five years? After some frustrating months of indecision, the Institute administration accepted this proposal, and Jefferson Tester ('71) was recruited from Los Alamos to be Class of 1942 Professor and director of the Practice School. Tester never studied in the Practice School, but he had served two years as a station director after completing his doctorate at the Institute, and his enthusiasm for the Practice school was unbounded.

During his first year as director, Professor Tester

- Changed the SCEP curriculum so that the School could serve three groups of students: outstanding undergraduates who would study for five years at the Institute, including one term at the Practice School, and receive both bachelor's and master's degrees; M.I.T. doctoral students, who would study for a one term at the Practice School in order to gain a sense of industrial practice available to few ScD and PhD candidates; and graduate students who, after completing undergraduate degrees elsewhere, would come to M.I.T. for master's degrees in chemical engineering practice, studying for two terms in Cambridge and one summer at the Practice School stations and thus making SCEP a year-round activity.
- Raised the salaries of Practice School station directors so that they related not to faculty salaries at M.I.T. but to industrial salaries for people of comparable experience in the plants in which they served.
- Increased the budgets of SCEP's stations to include travel and some of the professional/social occasions that animated the Practice School of the 1930s and 1940s, when the Eastman funds had been available.
- Raised the visibility of the Practice School by a variety of strategies that reflected Tester's confidence in and enthusiasm for the program.
- Worked with alumni and M.I.T.'s fund-raising apparatus to catalyze two separate fund-raising efforts. The first reactivated the Friends of the

*Photograph by Barry Hetherinton, from M.I.T. Museum*

*At the Practice School's 75th anniversary celebration in 1991 are (left to right) David Koch ('63) of Koch Industries, Inc., Jean Leinroth ('48), director of summer stations at Syntex Chemicals and Chevron, and Professor Jefferson Tester ('71), Practice School director from 1980 to 1989.*

*Photograph bvy Carole Williams, from* Chevron Focus

*Shown here on their first day at the Richmond (California) Station, students tour the Chevron Refinery, 1989.*

Practice School organization (Robert Richardson, '54, then executive vice-president of Du Pont, became chairman) to fund for several more years the corporate-sponsored fellowships first established in 1980. The second—and far more ambitious—effort was to raise from individual donors (corporate gifts were not solicited) an $8 million endowment to permanently underwrite fellowships for SCEP students during their Cambridge studies. This task was accepted by the Corporation's Visiting Committee, whose chair was Jerry McAfee ('40), retired chairman and chief executive officer of Gulf Oil Company.

Though it is far easier in the telling than it was in the doing, the final result was celebrated late in 1990 when the endowment was completed with a major gift from David H. Koch ('63) executive vice president of Koch Industries, Inc., leading to the School being renamed in his honor. "There was nowhere else in my M.I.T. experience," Koch told me, "where I had the chance to test my technical abilities, and I figured any educational experience that was this powerful for me might be of similar value to others."

With the endowment complete, the David H. Koch School of Chemical Engineering Practice entered the 1990s with its annual funding of about $1.3 million coming roughly in equal parts from endowment income, host companies, industrial fellowship grants renewing those obtained by the Friends, and M.I.T. resources. The endowment income and industrial grants cover stipends for Practice School students while studying in Cambridge; the host company funds are used by M.I.T. for fellowships for students at the stations, and Institute funds cover SCEP faculty salaries and benefits and administrative expenses.

As of 1993, the David H. Koch School operates year-round stations at Dow Chemical Company and neighboring Dow-Corning Company, Midland, Michigan, and Merck and Company's pharmaceutical operations at West Point, Pennsylvania. Annual enrollment is typically between thirty and forty, and the waiting list extends well into 1994. Each student spends eight weeks at each station, normally working on two four-week projects in two different groups. Thus each student has the experience of group leadership once during his or her term at the stations.

Essentially all M.I.T. Master's candidates in chemical engineering attend the Koch School, and two-thirds of all Doctor's candidates do so. Its director is T. Alan Hatton, Chevron Professor of Chemical Engineering at M.I.T., whose enthusiasm for the Practice School was developed as a station director during the summers of 1983 and 1984.

Perhaps the best recent summary of the School's status was given by Professor Jeffrey Feerer, associate director of SCEP from 1989 to 1992, at a 1990 conference on national materials policy: "For almost seventy-five years this chemical engineering internship program has directly transferred innovation and technology from the universities to the production floor, and it has educated chemical engineering students to the specialized and complex problems of chemical manufacturing. In doing so, it has provided a unique link between the narrowness of graduate chemical engineering education and the breadth of activities in which chemical engineers participate in the workplace.

"The Practice School is today more vibrant than at any time in its history, thanks in part to a legion of alumni/ae who celebrate the value that the Practice School experience has had in their careers."[5]

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**ChE educator**

# Michael B. Cutlip

## of the University of Connecticut

*by Lucinda Weiss**

The teaching "bug" bit Mike Cutlip at an early age. He was taking sophomore calculus at Ohio State University in 1960 when his teacher, Margaret Jones, inspired by the way he explained problems at the board, asked him to teach an introductory math class. He did such a good job that he was subsequently hired as a "student assistant" to help teach algebra and trigonometry at OSU. On spring breaks, when others headed to Fort Lauderdale for fun and games, he went home to Milford, Ohio, a suburb of Cincinnati, and taught math or science at the high school as a substitute teacher when the opportunity arose.

*Cutlip and his father, Sidney, representing (so far) over seventy-five years of teaching.*

"I liked it. It kind of got me started in teaching," he recalls.

It began a career devoted to chemical engineering education in which Cutlip has combined a research interest in catalytic reactions with computer-based, self-paced educational programs for chemical engineering students. He has coauthored personal computer software that is presently used by more than one hundred chemical engineering departments, and he is president of CACHE Corp., a non-profit organization based at the University of Texas, Austin, which promotes the application of computing technology to chemical engineering education.

When Cutlip started taking chemical engineering courses at OSU, the slide rule still represented the prevailing technology. He majored in chemical engineering in a five-year program that combined the bachelor's and master's degrees. Joseph H. Koffolt was the department chairman at the time, and he was known for remembering all his student's names and calling them "his jewels." Cutlip still runs into his former classmates on occasion. "There are still a few gems around," he says.

But an even earlier influence on his decision to teach was his own father. Sidney Cutlip was the high school principal and was Mike's algebra teacher at Milford High. He, too, had started teaching at nineteen—in a one-room school that included all eight grades. He worked on his bachelor's degree during the summer months and eventually earned his master's degree. Now eighty-five and retired, his teaching career spanned forty-four years.

"I have a lot of respect for my father," Cutlip says.

Cutlip's high school chemistry teacher, Mary Moore, encouraged him to pick a profession such as chemical engineering. "Initially, I thought of high school teaching, but she encouraged me to consider other options as well," he says. One of those options was aeronautical engineering, but Cutlip particularly liked freshman chemistry and had the lucky foresight to reject aeronautical engineering as too dependent on government grants.

He also decided to study for a PhD so that he

* 128 Davis Road, Storrs, CT 06268

could eventually do research or teach, hoping to eventually expand his horizons beyond the Midwest. During one spring break at OSU he fortuitously visited the University of Colorado where Max S. Peters was the new Dean of Engineering. Peters was very supportive of young Cutlip's goals and later became Cutlip's PhD adviser.

But it was a ski-run down Aspen Mountain that clinched Cutlip's decision to attend graduate school at the University of Colorado. Cutlip and a fellow OSU chemical engineering student, Alkis Constantinides (now a chemical engineering professor at Rutgers University) had learned to ski on Ohio's Mt. Mansfield. He says, "For a guy who had skied before but who had only experienced a vertical drop of about 150 feet, skiing from the top of Aspen Mountain was an unforgettable experience!"

Cutlip did both his graduate and post-graduate work at Colorado, studying the catalytic properties of polymeric materials and looking for new catalytic materials. Cutlip points out that his adviser, Peters (who continued as Dean and who became vice president and then president of AIChE in 1967 and 1968), was good at delegating responsibility and often asked the graduate students to help write reports and develop proposals in addition to conducting their research. "What I learned from him was organization," Cutlip says.

Peters also helped Cutlip find his first teaching position. In 1968 Cutlip became assistant professor at the University of Connecticut, and was later appointed associate professor, then professor—and for "nine long years," he jokes, he was department head. He stepped down from that administrative post in 1989.

New England was quite a change of pace for Cutlip and his wife, Susan, who grew up in Denver and met Mike at the University of Colorado. On his first visit to UConn, Cutlip was surprised by its rural character. "I thought it would have been paved from New York all the way up through Connecticut," he says. When he got back to Colorado from that initial visit, he told Susan that he had driven around the area a little bit, "but I didn't see downtown Storrs." He didn't realize that "downtown" Storrs was a small grocery store, a movie theater, and a traffic light!

The chemical engineering department at UConn, then headed by Leroy Stutzman (now retired), was still relatively young, having seen its first students graduate in 1963. Cutlip pursued his interest in reaction engineering, applying catalysis to air pollution control. Among his projects at UConn has been a long-standing interest in the electrochemical processes in hydrogen/oxygen fuel cells and in looking for ways to improve their efficiency. As a result of this interest, he is heavily involved with the Pollution Prevention Research and Development Center, a new center in UConn's Environmental Research Institute that is supported by the EPA.

***Cutlip developed a self-paced, mastery-oriented course in reaction engineering for seniors. [They] could come into the computer lab at any time, go through the tutorials at their own pace, and then take assignments and quizzes as they were ready for them.***

When he came to UConn, he was encouraged by Stutzman, who was a consultant and later a board member at Control Data Corporation, to research the potential of computers in education. Stutzman introduced him to CDC's PLATO (Programmed Logic of Automated Teaching Operations) system, and they looked into using it for self-paced, individualized instruction. "I feel fortunate that I've been able to do both lab research—hard-core research—and educational research projects simultaneously," Cutlip said. "There are not a lot of environments where that can be accomplished."

Cutlip developed a self-paced, mastery-oriented course in reaction engineering for seniors. The students could come into the computer lab at any time, go through the tutorials at their own pace, and then take assignments and quizzes as they were ready for them. They could send and receive messages from the teacher and work out intricate problems using a touch-sensitive screen. Cutlip points out, "We could keep track of each student and pose problems for them. We could tailor each problem for each student."

Between the computer time involved and the hiring of programmers, it turned out to be a very expensive developmental project, but it determined Cutlip's focus as a teacher. "I definitely like the concept of self-paced learning and mastery, giving the student a choice of educational activities. It's quite different from a one-way lecture where the student is passive," he states.

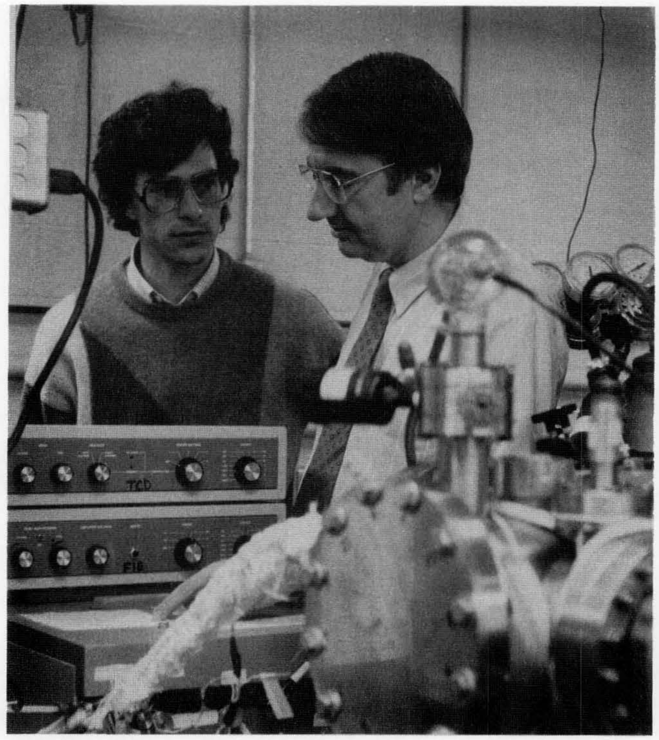
Computer-based instruction also helps chemical engineering students deal with the demands of their curriculum, he believes. The chemical engineering curriculum tends to be one of the most rigorous at a university, he notes, involving extensive math, engineering, and chemical engineering courses, with a continually growing load of course work being squeezed into the same amount of time. He feels that requiring students to have a personal computer to use for tutorials would enrich their understanding of the course work.

Cutlip believes that the growing use of CD ROMs for personal computers will accelerate the development of computer-based learning methods. "We can get 650 megabytes of information on that little disk. It's a real educational challenge—what to put on it to enhance the educational process." He adds that CD ROMs could also be used for process design packages, for a physical properties data base, or for instructional modules that would serve as enrichment activities; health and safety training is another potential use. He points out that as students become more computer literate earlier in their education, computer-based course work will become a much more common approach to teaching.

One way to involve computer-based learning in chemical engineering education was developed by Cutlip and co-researcher Mordechai Shacham of Ben Gurion University in Israel. They developed a numerical analysis package, POLYMATH, that allows chemical engineers to use various numerical methods to solve chemical reaction problems on a variety of personal computers (Cutlip has both an IBM and an Apple in his office and uses both actively). Since it was developed ten years ago, POLYMATH has been refined and improved in several versions and is now widely used by chemical engineering departments. It is site licensed, so it is easily shared throughout a department by both faculty and students.

"In my view, if we provide students with the right general-purpose software, we can propose more realistic problems for them to use in their homework," Cutlip says. The homework could be more representative of actual industrial problems because the computer would allow the use of more complex numerical methods, and theory could then be taught in more detail. He adds, "It's a big opportunity for enhancing the educational process."

POLYMATH is distributed by CACHE, which develops educational products and supports projects that promote computer-aided chemical engineering education. One of CACHE's biggest successes in its twenty-three years, says Cutlip (who is in the first year of a two-year presidency of the non-profit organization), has been the introduction of computer-aided process design (via FLOWTRAN) with the help of the Monsanto Chemical Corporation. Recent CACHE activities include participation in three curriculum development projects (with National Science Foundation support) at the University of Michigan, Purdue University, and the University of Washington. Cutlip also is leading CACHE's effort to produce the first CD ROM for an educational discipline and has encouraged a new effort in advanced computing.


*Cutlip and one of his former graduate students, Angelos Efstathiou, who is now doing teaching and research at the University of Patras in Greece.*

Cutlip views the computer as a tool—much as the slide rule and the electronic calculator which preceded it—that aids students in mastering the material but which does not diminish the role of the teacher. He is actively involved with his students; they pop in and out of his office constantly. He greatly admired his own teachers, such as Peters, who were accessible to students even when they had heavy administrative responsibilities, and he has vowed to continue that tradition.

During the past semester Cutlip taught a graduate chemical reaction engineering course and the undergraduate laboratory. He is also the AIChE student chapter advisor for the second time in his UConn career (he served for six years the last time) and recently helped the students organize and host the New England Regional AIChE student chapter meeting.

He has been active in the local AIChE chapter himself, serving as chairman and vice chairman of the Western Massachusetts Local Section (which includes eastern Connecticut) and winning its Diamond Jubilee Award in 1983. He won the Ralph R. Teetor Award for Outstanding Teaching Record from the Society of Automotive Engineers in 1974 for his work in helping engineering students at UConn develop and engineer a prototype catalytic converter device for an urban car (before these were required on automobiles).

Cutlip has also been awarded fellowships to study and teach in the United Kingdom and in Japan. In 1990 he went to Japan to work on fuel cells and also gave seminars at six universities on interactive numerical methods in chemical engineering education. At his host institution, Yamanashi University, he held afternoon teas for Japanese students, giving them an opportunity to practice their conversational English. He observes that students in Japan have more day-to-day direction from their faculty advisers but less interaction in lectures than do their American counterparts.

He has taken two sabbaticals at Cambridge University in England (1974 and 1983) and regards Cambridge as his "second academic home." He first worked there with Dr. Nigel Kenney, and they have since shared post-doctoral researchers, graduate students, and research projects using computers in catalysis-related work. One result of their work, using gradientless reactors to study the oxidation of CO and hydrocarbon mixtures, was that they were among the first to determine that these reaction systems would oscillate or change with time in a repetitive way. They published and described mathematically and physically why this happened.

Another project that Cutlip developed at UConn as a result of this collaboration involved periodic reaction operation and the finding that the reaction rate can be enhanced by feeding in one reactant and then another, alternately instead of all at once.

While at Cambridge, Cutlip was a member of Fitzwilliam College, participating in college activities and learning how the English university system works. He found that the colleges allow faculties of different departments and interest to interact and get to know one another's fields.

The Cutlips also enjoyed living in a small village near Cambridge, where their son attended school and where Cutlip was elected to the PTA/school committee. Susan, who is an accomplished musician and plays the violin in chamber groups and orchestras in eastern Connecticut, was invited to play in both the Cambridge University Orchestra and the Cambridge Symphony while they were there.

Sabbaticals are one of the really great benefits of a university position, offering an opportunity to see how educational systems work and how societies function in other countries, Cutlip observes, adding "Chemical Engineering is a pretty small group of professionals at the academic level, and sabbaticals let you get to know people around the world." His

*Cutlip and some of his Japanese students.*

most recent sabbatical was at the University of Adelaide in Australia in 1989, working with John Agnew, who is the chemical engineering department chairman there and who also worked in Cambridge with Kenney.

Before leaving for Australia, Cutlip stepped down from a nine-year tenure as department head at UConn. Although he jokes about the demands of that job, he confesses he "really enjoyed it—it's one of the most, if not *the* most important job at the university." It requires interfacing with so many varied groups, he notes—parents, prospective students, faculty, students, graduates, deans, administrators, business and industry, government, and accreditation bodies. "You are at the center of the network that really makes the university go," he says.

The chairmanship also offers an opportunity to have an impact on the curriculum and to recruit and nurture new faculty. One of the interesting contrasts of the job, he says, is trying to get the faculty to pull together as a cohesive group, yet encouraging faculty members to work on their own projects independently. "You have to be very persuasive in order to get all this to work," he declares.

Ultimately, Cutlip's primary career interest in chemical engineering has been teaching. As one who began teaching at nineteen and who is now fifty-one, he is likely to surpass his father's record in front of the blackboard. Or, perhaps more aptly, in front of the computer screen. ❐

ChE on teaching . . .

# SEVEN RULES FOR TEACHING

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After forty years of being a university professor, I would like to think that I have learned something about the art of teaching. From time to time younger colleagues and teaching assistants have asked me for advice on how to teach. My suggestions to them can be summarized in terms of three DON'Ts, three DO's, and one REMEMBER.

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## *DON'T . . . SHOW OFF*

Many teachers, either intentionally or unintentionally, seem to enjoy inflating their egos by trying to impress the class with their own brilliance or with their own recently acquired knowledge. Although a few particularly gifted students may be challenged by this display of erudition, most students will be confused or disgusted—or both. A teacher can be colorful without showing off, and colorful, lively teachers are much appreciated. It is important that the teacher conduct the course at a level commensurate with the students' background. Teachers also have to be very careful not to be condescending.

## *. . . BLUFF*

Beginning teachers often feel embarrassed when they are asked questions that they can't answer. Feeling that their lack of knowledge may make them appear inadequate, they then try to escape by bluffing. Sooner or later their dissembling will be discovered, and the students will lose respect for them. It is far better to admit ignorance and promise to find out the answer to the question by the next class meeting. A challenging question from a student can often be a wonderful learning experience for both the teacher and the class. Keep in mind, too, that there may well be one or more members of the class who are actually brighter and better informed than the teacher; such students will find the teacher's bluffing contemptible.

## *. . . INTIMIDATE*

All of us have at one time or another been victims of a tyrannical teacher who appears to derive pleasure by making students feel uncomfortable or inadequate. Such teachers create a hostile atmosphere and thereby make the learning process difficult. Students will be hesitant to ask questions if they are told that their questions are ridiculous. Students should be encouraged to ask questions, and they should be answered patiently and carefully. The class should be reminded of the Japanese proverb: *Kiku wa ichiji no haji, kikanu wa matsudai no haji: To ask is a moment of shame; not to ask is an eternity of shame.* Teachers should be demanding, but they should not embarrass or ridicule students either in public or in private. They should always treat students with courtesy and respect.

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## *DO . . . KNOW WHAT YOU ARE GOING TO TEACH*

It may seem unnecessary to remind teachers that they should know the subject material thoroughly. It is not enough just to have read the textbook before going to class. We all know that even the best textbooks contain misprints, factual errors, and unclear passages. The good teacher will have read other textbooks, some primary sources, some review articles, or perhaps some recent research papers in order to have a depth of understanding well beyond that needed for the classroom presentation. He will also spend some time thinking independently about the subject material in order to develop a deeper understanding and even novel viewpoints. This is time consuming, but ultimately very rewarding.

### . . . *KNOW WHY YOU ARE GOING TO TEACH IT*

Students have to be motivated in order to learn new material. If they know why they should learn a particular subject and how they can apply the newly learned material, they will be more enthusiastic and receptive. It is therefore essential that the teacher be well aware of the scientific and engineering relevance of each topic; if a topic is not important, then it does not merit inclusion in the syllabus. It is also very important to discuss how the topic being presented is related to subject material in other courses in the curriculum. Many teachers are discouraged when students seem to be unaware of the connections between different courses, and yet they do very little themselves to emphasize these connections. Since students do have problems with carry-over between courses, it is quite appropriate to take a few minutes to review a topic from another course by prefacing the comments with something like "As you will recall from your course in thermodynamics . . ."

### . . . *KNOW HOW YOU ARE GOING TO TEACH IT*

It is not enough to master a topic before teaching it. Considerable thought must also be given to the mode of presentation—questions and answers, discussion of homework problems, visual aids, and library assignments are just a few of the many alternatives to straightforward lecturing. The sequencing of the material also requires careful consideration; for example, should one start with a general statement and then give illustrative examples, or is it preferable to give some examples first and then proceed to a general statement? Symbols and notation should be carefully chosen for the optimum mnemonic value. Making a subject easy to learn requires originality and artistry. One of a teacher's most important jobs is to figure out how to take a massive amount of difficult material and present it in an orderly, easy-to-understand way. An excellent motto for a teacher is: "Eschew obfuscation!"

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## *REMEMBER . . .THE TEACHER'S JOB IS TO SERVE THE STUDENT*

Students pay money for being taught, and teachers receive money for teaching. The teacher has a contractual obligation to provide the best possible guidance to those who are entrusted to him. This includes high quality lecturing, careful mentoring, career guidance, and in some instances a willingness to help with personal problems. It also includes the maintenance of standards and informing students frankly and honestly when their performance is unsatisfactory; the teacher does not help students by being a crowd-pleaser or by rewarding poor performance. The teacher's responsibility does not stop with the end of the semester, or even with the student's graduation. Years later the teacher may be called upon to provide help in connection with a former student's job application, his aspiration to a position with more responsibility, or his consideration for an award or prize. The student-teacher relation can evolve through the years into a lasting friendship, with all the rewards that such a relationship implies.

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I have arrived at the above simple rules after many years of classroom teaching, student advising, and textbook preparation. At various times I have broken all of the above rules, and I have suffered the consequences. The rules are hard to follow, but it helps to have some guidelines.

*(I would like to thank Professor C.G. Hill, Mr. Atul M. Athalye, and Mr. Peyman Pakdel for constructive comments.)*

# THE TECHNICALLY FEASIBLE DESIGN

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**Introductory Note**

*It is frustrating to attempt to capture effective classroom experiences in an article, but I am tempted to try again to do so because this past year I had the very rewarding experience of supervising a DuPont Teaching Fellow* (Ms. Linda Broadbelt) while team teaching a junior level chemical engineering course in reaction and reactor design with Dr. N. Orbey, a visiting professor at the University of Delaware from Middle East Technical University (Turkey). Their enthusiasm for the "technically feasible design" approach has prompted this paper. It is my hope that it will encourage classroom experimentation and help educate students about design problems.*

**— TW Fraser Russell**

Chemical engineers design, build, operate, and modify process equipment, or carry out the research necessary to do so more creatively and more efficiently. Not all chemical engineers are directly involved in the art and science of design, but all chemical engineers are exposed more or less effectively to various aspects of design in the educational programs in our universities. Indeed, it is part of our profession's criteria for accreditation, as shown by Section IV.C3(a) of "Criteria for Accrediting Programs in Engineering in the United States":

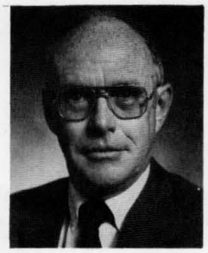
> (IV.C.3(a)) Engineering Design
>
> (a) Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective.

and by the "Program Criteria for Chemical and Similarly Named Engineering Programs":

> Engineering Design. (Amplified criteria section IV.C.2.d(3))
>
> The various elements of the curriculum must be brought together in one or more capstone engineering design courses built around comprehensive, open-ended problems having a variety of acceptable solutions and requiring some economic analysis.

These legal sounding criteria, which attempt to define design content, do not give us any insight into the value of design as a tool for making courses more intellectually challenging or more interesting. In fact, the "Chemical Engineering Criteria" which calls for a "capstone" design course has been interpreted by some educators as allowing them to ignore design until the final year of a four-year program in chemical engineering.

We tend to educate in the early years of the curriculum by using ideal technical problems in our courses. The ideal technical problem is one in which all the information is given and for which a single correct answer is most frequently obtained by solving an equation or sets of equations. Much effort is expended, both by professors in class and by students doing homework, on mathematical manipulation. While this serves a purpose in that it helps teach problem-solving methodology, it tends to pro-



**TW Fraser Russell** *is the Allan P. Colburn Professor of Chemical Engineering and Director of the Institute of Energy Conversion, a laboratory at the University of Delaware devoted to thin-film photovoltaic research. He received his BSc and MSc degrees from the University of Alberta and his PhD from the University of Delaware, all in chemical engineering. He is the author of over seventy technical publications and is coauthor of two texts.*

**Nese Orbey** *received her BS and MS in chemical engineering from Middle East Technical University (METU), Turkey, where she is currently an associate professor, and her PhD from McGill University, Canada. She served as Visiting Associate Professor at the University of Delaware from 1990 to 1992. Her research interests are in the area of polymer rheology.*

* *The E.I. duPont de Nemours and Company's DuPont Teaching Fellows Program is designed to encourage graduate students to become interested in university-level teaching.*

duce students who do not understand that engineering problem solving and/or the creation of engineering opportunity must go beyond routine mathematical manipulation.

This serious difficulty can be avoided and students can be introduced to the art of engineering earlier in the curriculum if faculty would require that the students produce a "technically feasible design" rather than a single-answer solution to a problem.

**TECHNICALLY FEASIBLE DESIGN**

A technically feasible design is one which defines the size of a piece of process equipment to meet a stated goal, and in so doing initiates an analysis of the factors affecting optimal design. It could be specification of the volume for a reactor, the total area for an exchanger, or the height and diameter of a separation unit. The use of a technically feasible design can be illustrated for chemical engineering students by considering a simple problem in chemical reaction engineering.

Chemical engineers frequently become involved in a reactor-process design problem at an early stage, *i.e.,*

> How can our firm safely make a product ("D") for which there appears to be a good market at a fair profit?

While this is the type of problem that we would like a chemical engineer to be able to solve, it is too open-ended for students in their first few years of study. It is time-consuming and difficult even for many faculty to do. It also disrupts the logical flow of subject matter to introduce the issues of market development, competitive market-share pricing, and capital and operating cost estimating which are necessary to solve the problem.

The following is a simple, technically feasible design problem that can be presented to the student:

> Our firm has determined that we can sell 1260 metric tons/year of product "D," a raw material for the manufacture of an important fiber. "D" has a molecular weight of 50 and the reactor is assumed to operate 24 hours a day, 350 days a year.
>
> Our laboratory has studied the homogeneous liquid phase reaction which produces "D"
>
> $$A + B \rightarrow D$$
>
> This reaction can be carried out isothermally in an excess of B with the kinetics determined as follows:
>
> $$r_{A-} = kc_A$$
> $$k = 0.005 \text{ min}^{-1}$$

The simplest possible technically feasible design can be completed if the student is told at this point to assume that the reactor will be a continuous flow stirred tank (CFSTR) with a feed stream concentration of A, $C_{AF}$ = 0.2 g-moles/liter.

***We tend to educate . . .by using ideal technical problems in our courses . . .in which all the information is given and for which a single correct answer is most frequently obtained by solving an equation or sets of equations.***

We have tested this problem with chemical engineering students in courses such as "Introduction to Chemical Engineering Analysis" and "Chemical Engineering Kinetics" and with a great many non-chemical engineers (mostly chemists and other engineers) in professional society-sponsored courses throughout the Delaware Valley. So far, over two thousand students have been asked to carry out this technically feasible design in class.

At the stage in any course when we introduce this exercise, the students are capable of deriving the required mass balances:

species A $$0 = qC_{AF} - qC_A - kC_AV \tag{1}$$

species D $$0 = 0 - qC_D + kC_AV \tag{2}$$

The technically feasible design is required for

- $C_{AF}$ = 0.2 g-moles/liter
- $k = 0.005 \text{ min}^{-1}$
- total production of 1260 metric tons/year ($qC_D$ = 50 g-moles/min, or $2.52 \times 10^7$ g-moles/year)

We ask students to carry out this exercise during class so we can observe their thought processes and can thus generate more effective discussion. When the exercise is introduced, the students are told that the design will be considered complete when the reactor volume, V, has been determined.

In order to maximize the educational gain for both the instructor and the students, the class should work unaided on the design for about thirty minutes, with each student attempting to obtain the reactor volume, V. We have found that students rarely obtain the reactor volume on their own without additional class discussion. A walk around the classroom, observing how the students attempt to carry out this very simple design, is most instructive. They will manipulate and remanipulate Eqs. (1) and (2) in an effort to obtain V. It has never been clear to us why almost all students do this, since counting unknowns and equations clearly shows that one variable in addition to those given must be specified. (Students should have done enough algebraic manipulations by this time in their academic lives to be thoroughly familiar with solutions of such a simple system of equations.)

Students are often reluctant to complete the technically feasible design by selecting values for the variables, q or $C_A$, probably because they have been taught to solve problems in which they had to derive and manipulate equations to obtain a solution. A very simple design decision (*i.e.,* select a value for $C_A$, the exit concentration of raw material A, and determine reactor size V) turns out to be foreign to the student's whole experience in problem solving.

To achieve a technically feasible design by assuming a value for q or for $C_A$, it is convenient to rearrange Eqs. (1) and (2). The most effective way to compute a reactor volume, V, is with Eq. (2):

$$V = \frac{qC_D}{kC_A} \tag{3}$$

$$V = \frac{50}{0.005\,C_A}$$

Since $C_A$ can only vary between $C_{AF} = 0.2$ g-moles/liter and 0, the student can quickly obtain a technically feasible design. For example, if $C_A = 0.1$ g-moles/liter, then V = 100,000 liters.

If the students are encouraged to experiment with the set of equations, about a third of them will eventually derive Eq. (3). Others will assume a value for q, calculate $C_D$ from $qC_D = 50$ g-moles/min, obtain $C_A$ from $C_{AF} - C_A = C_D$ (the addition of Eqs. 1 and 2), and then solve for V using either Eq. (1) or Eq. (2). This more involved approach has the disadvantage that limits on the value of q are not as obvious as limits on the value of $C_A$. For instance, if q is assumed to be 200 liters/min

$$C_D = 50/200 \quad \text{and} \quad C_A = 0.2 - 0.25 = -0.05$$

Obviously, $C_A$ cannot be negative, so q must be greater than 250 liters/minute for a technically feasible design ($q \quad qC_D/C_{AF}$).

The problem is discussed in more detail in *Introduction to Chemical Engineering Analysis,*[1] and the role of the technically feasible design in initiating an analysis of the factors affecting optimal design is illustrated in Table 1.

It is very important to again stress that almost all the educational impact of the technically feasible design concept is lost if students do not have an opportunity to work on the problem by themselves in a classroom setting, with an instructor who is willing and capable of initiating discussion. Table 1 shows that the optimal size of a reactor cannot be considered without also considering how unreacted A is separated from product D. It also shows students how the reactor analysis affects the downstream process design. A large reactor with a small concentration of A in the effluent (high conversion) costs more than a small reactor with a large concentration of A in the effluent (low conversion). If a customer can use D with a small amount of A present, then it might be possible to eliminate an A-D separation unit which requires an expensive reactor. To reduce reactor costs one must pay for the capital and operating costs of the separation unit.

**TABLE 1**

| q (liters/min) | $C_D$ (g-moles/liter) | $C_A$ (g-moles/liter) | V (liters) | $\theta$=V/q (mins) |
|---|---|---|---|---|
| 250 | 0.200 | 0 | $\infty$ | $\infty$ |
| 300 | 0.167 | 0.033 | 303,000 | 1000 |
| 400 | 0.125 | 0.075 | 133,000 | 333 |
| 500 | 0.100 | 0.100 | 100,000 | 200 |
| 800 | 0.0625 | 0.1375 | 72,600 | 90.7 |
| 1000 | 0.0500 | 0.1500 | 66,600 | 65 |
| 2000 | 0.0250 | 0.1750 | 58,100 | 27 |
| 4000 | 0.0125 | 0.1875 | 53,200 | 13.3 |

**TABLE 2**

| $C_A$(g-moles/liter) | $C_D$(g-moles/liter) | t(min) | batches/year | V(liters) |
|---|---|---|---|---|
| 0.01 | 0.19 | 599 | 700 | 190000 |
| 0.05 | 0.15 | 277 | 1269 | 133000 |
| 0.10 | 0.10 | 139 | 1945 | 130000 |
| 0.15 | 0.05 | 57.5 | 2839 | 178000 |

An "optimal" design is discussed in *Introduction to Chemical Engineering Analysis.* Also, a process design game that has been widely used and which very effectively illustrates the economics and introduces the concept of competition is described in a paper titled "Teaching the Basic Element of Process Design with a Business Game."[2]

The CFSTR technically feasible design problem can be used with students at any level in the curriculum (when providing Eqs. 1 and 2, we have even used it with high school seniors and first-semester freshmen). We expect University of Delaware chemical engineering majors to be able to derive Eqs. (1) and (2) after their sophomore year.

The design problem is used throughout the junior-level chemical engineering kinetics course, and we require that the students carry out a commercial-scale technically feasible design for the following reactor design situations:

- CFSTR (isothermal single reaction)
- batch reactor (isothermal single reaction)
- semi-batch reactor (isothermal single reaction)
- tubular reactor (isothermal single reaction)
- CFSTR and tubular reactor (isothermal series-parallel reactions)
- CFSTR (non-isothermal)

## EXAMPLE: BATCH REACTOR

The technically feasible design for the batch reactor requires significantly different thinking, even though the same problem is addressed. The students are expected to derive the pertinent material balances

$$\frac{dC_A}{dt} = -kC_A \tag{4}$$

$$\frac{dC_D}{dt} = kC_A \tag{5}$$

and solve the differential equations

$$\ell n\left(\frac{C_A}{C_{Ao}}\right) = -kt \tag{6}$$

$$C_D = C_{Ao} - C_A \tag{7}$$

At this stage the problem differs from the CFSTR example in that the volume V for a technically feasible design cannot be directly obtained since the material balance equations for the batch reactor do not contain a volume term. Reaction time, t, must be obtained from Eq. (6) and then used to obtain the reactor volume.

Again, students need to work on their own in a classroom setting and must be given an opportunity to discuss the design with the instructor. Most students have difficulty obtaining the reaction time despite having encountered a similar situation with the CFSTR design. Equation (6) has two unknowns: $C_A$ and t. The value of t can only be solved as a function of $C_A$, and any pair of t-$C_A$ is one solution leading to a technically feasible design. Students must assume a value for $C_A$ just as they did in the CFSTR example. For example, if $C_A = 0.1$ g-moles/liter

$$t = 138.6 \text{ min and } C_D = 0.1 \text{ g-moles/liter}$$

Students must also make additional judgments to obtain a technically feasible design. The total yearly production is known and the volume of the reactor is related to the reaction time.

$$2.52 \times 10^7 = (VC_D)\,(\text{Batches/year}) \tag{8}$$

Both $C_D$ and the number of batches per year that can be processed depend on the reaction time (Eqs. 6 and 7).

$$C_D = C_{Ao}(1 - e^{-kt}) \tag{9}$$

To find the total time in hours to process a batch, time for charging raw materials, removing product, and cleanup must be considered in addition to the reaction time. We can then obtain V from Eq. (8) by assuming there are 350 x 24 hours in a year. The results of some sample calculations for technically feasible values of V are given in Table 2, assuming that the time for charging raw materials, removing product, and cleanup is two hours.

Table 2 also provides information for a discussion of the important factors in any optimal design. The optimal size of the reactor depends on downstream processing. In the case of a CFSTR, volume decreases monotonically as conversion decreases (see Table 1). Batch processing is a labor-intensive process. At very low conversions ($C_A = 0.15$) with low reaction time, the time required for charge and cleanup (two hours) is almost twice that of the reaction time. The reactor volume is thus greater than for $C_A = 0.10$.

In the CFSTR, low conversions had the advantage of low reactor capital cost and the disadvantage of high separation costs. In the batch process, low conversion leads to the double disadvantage of high reactor capital cost and high separation costs.

In Table 2, batches/year are given, but in classroom discussions either batches/day or batches/shift can be computed to promote discussion on the issues of labor requirements and costs.

## CONCLUSIONS

The importance of design in chemical engineering education has been effectively taught to both chemical engineers and chemists by requiring students to complete simple, technically feasible designs in class.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

- C species concentration, g-moles/liter
- k specific reaction rate constant, $min^{-1}$
- q volumetric flow rate, liters/min
- $r_A$ rate of reaction, g-moles/liter, min
- t time, minutes
- V reactor volume, liters

***Subscripts***

- A,D chemical species
- F feed condition
- o initial condition

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# PROCESS CONTROL EDUCATION
## *A Quality Control Perspective*

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There are a number of issues that warrant an examination of the current undergraduate course in process control. One is the notion of statistical quality control being used in industry. Statistical process/quality control (SPC/SQC) concepts[1] grew out of the discrete manufacturing environment as a response to competitive pressures, and current efforts aim at the notion of *zero defect.* In recent years, SPC concepts have also made their presence felt in the continuous-process industries,[2-4] and concepts such as control charts, control limits, common causes, and special causes are now commonly used as measures of product quality variability as well as to detect problems and take corrective actions. Automatic correction when a defect is detected is beyond the scope of SPC, however, so the word "control" in the acronym is somewhat misleading. For the buyers of products from processing industries, SPC measures represent proper evidence of the variability of product quality, and these measures often form the basis of purchasing contracts. One consequence of the success of SPC is that excellent communication appears to exist between statisticians and company management.

Similar communication among process control professionals and management, however, appears to be lacking, and one of the contributing factors is control "jargon." The control engineer speaks in terms of servo and regulatory responses, input suppression and penalty parameters, model uncertainties, exponential filters, and robustness. While there is no implication that these are unimportant, to tie them to product quality (the primary concern of management) is often difficult. A proper understanding of the role of both statistical process control *and* engineering process control in achieving product quality would improve communication between statisticians, management, and control specialists, and would considerably enhance the ability of control specialists to have a stronger impact on process and plant operations. Students should be aware of the importance of this kind of interaction.

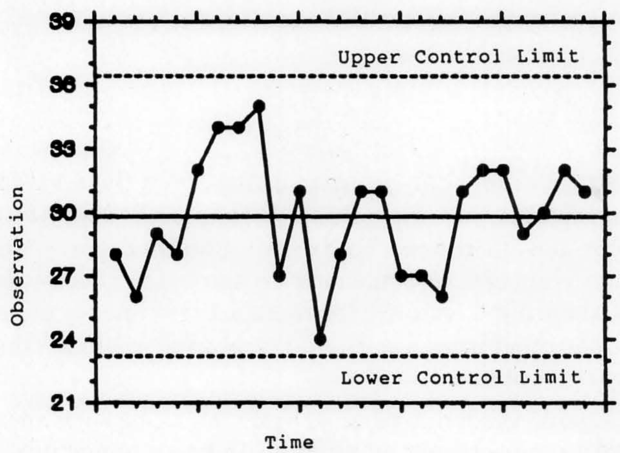
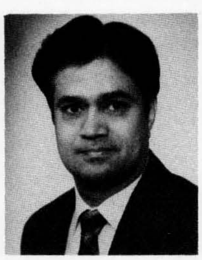



***Figure 1.*** *Typical control chart*

Consider the Shewhart control chart[5] of a hypothetical discrete parts manufacturing process, shown in Figure 1. In discrete-parts manufacturing, the adjacent data points are assumed to be statistically independent of each other. In fact, the data from a process under statistical control are deemed to follow a Gaussian (normal) distribution.

The mean of the data is the center line on the Shewhart control chart. In light of the assumption of normality, then, 99.73% of the data will lie within $\pm 3\sigma$ limits from the mean; the $\pm 3\sigma$ limits are the so-called statistical control limits. If the data points lie within the control limits and are more or less ran-



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*The control engineer speaks in terms of servo and regulatory responses, input suppression and penalty parameters, model uncertainties, exponential filters, and robustness. While there is no implication that these are unimportant, to tie them to product quality is often difficult.*

domly distributed, the variability is deemed to have been caused by *common causes.* Within the context of process control, common causes are those random disturbances whose detrimental effect upon product quality cannot be eliminated by any kind of control action. If a non-random pattern is detected, although the data points are within the control limits (*e.g.,* seven points in a row are above/below the central line, fourteen points in a row alternate up and down, etc.), there may be an *assignable (or special) cause* that should be investigated. Points outside the control limits are also said to have been caused by *assignable causes.* Assignable causes need to be investigated and corrective action must be taken.

In contrast, the data points on a chart similar to Figure 1, representing the quality variable from a continuous process and plotted as a function of the sampling interval, are invariably autocorrelated. Furthermore, the center line is the set point and not the mean of data points. The integral action in the controller will insure that the quality variable will return to the set point for certain types of disturbances. Thus, the closed-loop responses in the CPI do not obey statistical control concepts well. Recent research, however, has led to methods that can be used to analyze the autocorrelated data and make them amenable to statistical monitoring.

Process control practitioners have often obeserved that a *good* control algorithm is one which shifts much of the variability of an output onto the input, *i.e.* the manipulated variable.[6] In fact, an algorithm's performance is frequently measured in terms of its ability to shift the entire variability from the output to the input under ideal conditions.

An illustrative example of a heat-exchanger system taken from Downs and Doss[6] is shown in Figure 2. In this instance the control algorithm attempts to hold the exit temperature as closely as possible to the set point by suitably manipulating the flow of the heating medium. The ability to deliver offset-free performance is a key requirement in controller design. It has been pointed out that in industrial situations, manipulated variables often have their own processing units, and transferring an excessive amount of variability to them may not always be the the best approach. Thus, a control law

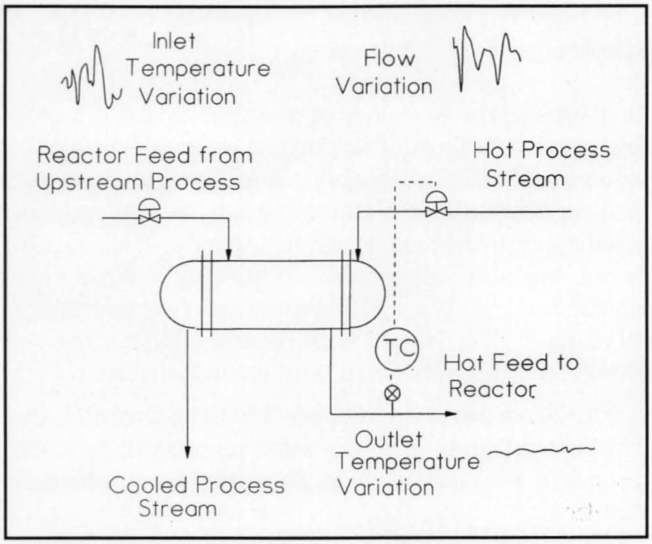


*Figure 2. A control algorithm shifts the variability of the output onto the input.*

should be designed so that only as much variability is transferred to the input as is necessary to produce a product of acceptable quality.

The foregoing discussion points out the need for suitable control laws and appropriate statistical tools which can handle autocorrelated output data for statistical monitoring purposes. We recently presented a unifying perspective that combines the best features of engineering process control (EPC) and statistical process control (SPC) for achieving total quality control of continuous process systems. In the following paragraphs we will briefly review the unifying methodology for EPC and SPC and will reveal what new material should be added to the traditional process control course to make it more effective in meeting the needs of industry.

## UNIFYING METHODOLOGY FOR ENGINEERING AND STATISTICAL PROCESS CONTROL[7]

We propose a two-part procedure for achieving total quality control of continuous processes. In Part 1, we design a suitable control law to hold the output (reflecting the quality variable) within specifications in the presence of load disturbances and modeling errors. In Part 2, we analyze and massage the autocorrelated output data so as to render them amenable to statistical monitoring. The usual SPC rules may then be applied to keep the continuous process under statistical control.

### Part 1
### Engineering Control Systems Design

Many approaches to control are described in the literature. Just which approach to use depends on the type of process and on the personal preference of the designer. The basic requirement is that the control law must hold the quality variable within specifications in the presence of disturbances and modeling errors. In light of our introductory discussion, it is obviously desirable that the control law contains tuning constants which can be adjusted to improve quality or to reduce costs, in terms of the manipulated variable movements, consistent with client specifications. We will here review two approaches to control: PID control with feedforward control and dead-time compensation, and stochastic control.

***The Standard Approach*** The standard PID controller continues to be the most popular in industry. the *ideal* PID controller is described by the transfer function

$$G_c(s) = K_c\left(1 + \frac{1}{\tau_I s} + \tau_D s\right) \tag{1}$$

There are several approaches to tuning this type of controller. Some of them involve open-loop testing, while others are based on closed-loop experimentation. The settings that result are meant to satisfy certain specified optimization criteria, such as minimum ISE (integral of the squared error), quarter decay amplitude ratio, etc.

The system performance deteriorates as dead-time in the loop increases. The notion of dead-time compensation is to remove the dead-time from the system's characteristic equation so that the system performance improves. There are two ways to achieve dead-time compensation: one (attributable to O.J.M. Smith[8]) is called the Smith predictor, while the other (attributable to C.F. Moore[9]) is called the analytical predictor.

In real-life applications, disturbances are invariably present. The controller must compensate for the negative effect of the disturbances on the process output. In those applications where disturbances can be measured, the notion of feedforward control may be employed. Figure 3 depicts the block diagram of the closed-loop system, showing PID control with dead-time compensation and feedforward control. The Smith predictor approach for dead-time compensation is shown in Figure 3 for illustrative purposes; Moore's analytical predictor may be employed instead if so desired. The arrangement shown in Figure 3 is industry standard. Blocks to implement PID control, lead lag, and dead-time compensation come standard with modern distributed control systems.

***Stochastic Controller Design***[10,11] We know that for identical model structures ($G_P$ and $G_L$) and identical closed-loop performance specifications (*e.g.,* minimum variance), there is really no difference between the design of feedback controllers for deterministic or for stochastic disturbances.[12] It is nevertheless important to be familiar with how controllers are designed for stochastic disturbances, because with this approach the closed-loop data can lend itself directly to statistical monitoring.

Consider a single-loop linear system that is perturbed by stochastic disturbances. A stochastic disturbance, called *noise,* is obtained by passing white noise, $a_t$ (having zero mean and a constant variance $\sigma^2_a$), through a suitable model structure such as a first-order lag, an integrating type load such as a ramp, etc. The disturbance model structure is selected so that it is representative of the real-life situation. In fact, plant testing with PRBS (pseudo random binary sequence) signals followed by time series analysis can help identify the models that would be needed for designing the type of controller being discussed in this section. The purpose of the exercise is to design a control law which will minimize the variance. The output of the system, $C_t$, is related to the manipulated variable, $M_t$, and the noise, $N_t$, according to

$$C_t = \frac{\omega\left(z^{-1}\right)}{\delta\left(z^{-1}\right)} M_{t-F-1} + N_t \tag{2}$$

where F is the time delay in terms of number of sampling periods.

Equation (2) can be equivalently written as

$$C_{t+F+1} = \frac{\omega\left(z^{-1}\right)}{\delta\left(z^{-1}\right)} M_t + N_{t+F+1} \tag{3}$$

For minimum variance control, $C_{t+F+1}$ must be set to

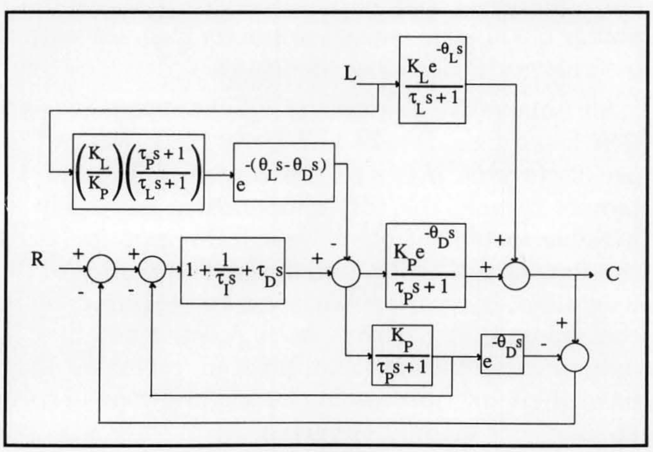


***Figure 3.*** *The standard approach.*

zero. Equation (3) then gives

$$M_t = -\frac{\delta(z^{-1})}{\omega(z^{-1})} N_{t+F+1} \tag{4}$$

The control law given in Eq. (4) cannot be implemented since it requires knowledge of $N_t$, F+1 sampling instants into the future. Since future information can only be forecasted, Eq. (4) must therefore be written as

$$M_t = -\frac{\delta(z^{-1})}{\omega(z^{-1})} \hat{N}_{t+F+1} \tag{5}$$

where the caret ^ denotes an estimated value. For illustrative purposes, we will assume that the noise model is adequately described by

$$N_t = \frac{\theta(z^{-1})}{\phi(z^{-1})\nabla^d} a_t \tag{6}$$

Usually, the parameter d = 0, 1, or 2. It permits the designer to describe non-stationary types of disturbances. Following the procedure for forecasting the disturbance (see Reference 7 for details) leads to the control law

$$\nabla^d M_t = -\frac{\delta(z^{-1})}{\omega(z^{-1})} \frac{L(z^{-1})}{\phi(z^{-1})} \frac{1}{\psi_1(z^{-1})} e_t \tag{7}$$

where

$$e_t = C_t - C_t^{set}$$

Equation (7) is the minimum variance stochastic control law for single-loop systems. The choice of minimum variance (deadbeat control) invariably leads to excessive manipulated variable movements, but this difficulty can be overcome by incorporating a filter ahead of the controller. Here, the filter constant can be adjusted to improve quality or to reduce costs. The procedure has been shown equivalently leading to the IMC scheme[13] with a filter.[12]

It can be shown[12] that substitution of Eq. (7) back into Eq. (2) for a case where F = 0 gives

$$C_t = a_t \tag{8}$$

That is, the closed-loop output data are distributed according to a normal distribution, having zero mean and a constant variance. Thus, the output data can be used directly in preparing control charts (Shewhart, CUSUM, etc.). It should be pointed out, however, that for processes with dead-time under minimum variance control, the data points every F sampling intervals need to be used for control charting since the autocorrelation reduces to zero at lag F in this instance. As previously pointed out, minimum variance cannot often be specified because it leads to excessive movements of the manipulated variable. Furthermore, the quality requirements in specific situations may not call for such tight control—in which case it would be wiser to select tuning constants that will dampen the oscillations. Under these situations, industrial experience suggests that the output data will be autocorrelated.[14,15] The question remains: how can the autocorrelated data be massaged so that SPC rules can be applied? We take up this topic in the following section.

## *Part 2*
## *Statistical Monitoring*

We assume here that the feedback controller has been designed and the tuning constants have been selected properly. Thus, we can surmise that the process operates under the command of the selected controller, producing a product of acceptable quality in the presence of load disturbances and modeling errors. We want to apply SPC techniques to maintain the continuous process under statistical control. We can assume that the variance is greater than the minimum and that the output data are autocorrelated. Attempts to apply the traditional SPC rules will result in false signals due to the highly autocorrelated nature of the data; that is, no assignable causes would be found.

Problems arising due to autocorrelation can be overcome in one of two ways. In the first approach an autocorrelogram is prepared, showing how the autocorrelation coefficient reduces with increasing sampling intervals.[16] From such a plot, a sampling interval may be selected for which the autocorrelation coefficient is sufficiently small. A control chart can then be prepared using the selected sampling interval to which SPC rules may be applied as usual to detect the presence of assignable causes and to maintain the process under statistical control. A potential drawback of this approach is that the selected sampling interval may be too large, meaning that the process could go out of control before the next data point becomes available.

In the second approach, the thrust is to fit an appropriate time series model to the observations and then apply the control charts to the stream of residuals from the model.[15] Thus, if $C_t$ represents the observation, and $\hat{C}_t$ represents the predicted value obtained from an appropriate model fitted to past data, then the residuals $e_t = C_t - \hat{C}_t$, representing the prediction error, will behave as independent and identically distributed random variables. Several time-series models have been suggested for this purpose. One is an autoregressive integrated moving average (ARIMA) model that is of the form

$$\phi_p\left(z^{-1}\right)\nabla^d \hat{C}_t = \theta_q\left(z^{-1}\right)a_t \tag{9}$$

Another basis is the exponentially weighted moving average (EWMA) statistic. In this instance, the sequence of one-step ahead forecast errors

$$E_t = C_t - \hat{C}_t(t-1) \tag{10}$$

are deemed to be independently and identically distributed and may be used to prepare control charts to which SQC can be applied as usual. Here, $\hat{C}_t(t-1)$ is the forecasted value of $C_t$ made at time instant t-1. The EWMA approach is said to have computational advantages over the exact ARIMA approach, but the former is adequate when the observations are positively autocorrelated and the process mean does not drift too quickly.

Having reviewed the unifying procedure for total quality control in continuous process industries, we will now discuss the issue of fault diagnosis and the corrective measures that can be invoked to remedy the situation. We assume that the designer has access to the run-time charts and the appropriate control chart pertaining to the quality variable under assessment.

A variety of assignable causes can lead to out-of-control points on the control chart. For some, the remedy is in the domain of instrumentation and control, while for others the remedy may lie elsewhere. Some commonly encountered assignable causes in the domain of instrumentation and control are

- Malfunctioning control valve and/or sensor
- Changes in dynamic process parameters such as gain, time constants, and dead-time due to equipment fouling, catalyst decay, etc.
- Increasing system nonlinearities.

## PROPOSED ADDITIONS TO COURSE CONTENTS

A number of excellent textbooks for undergraduate process control are available (a sampling is included in references 17 through 20 at the end of this article), and instructors typically cover a number of standard topics in the course (*i.e.,* the material in Chapters 1-16 of *Process Dynamics and Control*[18]). In light of the foregoing discussion, we feel the following material can also be added to the course contents.

➢ *Introduction to Process Control* It must be emphasized in the introductory chapters that the fundamental objective in process control is to produce products of a specified quality. Other aspects (such as maximizing throughput, environmental considerations, and safety) are extremely important, but the student should not lose sight of the fundamental objectives.

➢ *Statistical Process Control* A new chapter on statistical process monitoring should be introduced. Students need to understand the assumptions inherent in SPC—namely, normality of quality data. SPC measures (such as Shewhart and CUSUM charts) and concepts (such as common causes and assignable causes) need to be discussed, and the commonly used rules to detect out-of-control signals should be outlined.

➢ *Feedback Controller Design* During the discussion of the trade-offs between responsiveness and robustness in the controller design section, the instructor should introduce the new perspectives on trade-off between quality and costs, and the discussion should include a number of control laws that have the desirable properties. Since the design of control algorithms will require an appreciation of feedforward control and dead-time compensation, these concepts will also have to be introduced if they have not yet been covered.

➢ *Process Identification* The specified closed-loop performance can best be achieved when the process model accurately reflects the industrial plant. Pseudo random binary sequence (PRBS) testing is widely used by industry to identify plant dynamics. Time series analysis of the input-output data leads to transfer function models; step response models can also be evaluated. Because of predictable time limitations for instruction, we suggest that canned software packages be used to demonstrate the concepts.

➢ *Introduction to Stochastic Control* As previously mentioned, deterministic and stochastic design procedures will lead to the same control law for identical performance specifications and model structures. It is nevertheless desirable to expose the student to the basics of stochastic control. The important lesson here is that under ideal conditions, the closed-loop output obtained under minimum variance control has a normal distribution, and therefore it is directly usable in preparing control charts for statistical monitoring purposes. Here too, the instructor can highlight the trade-offs between quality and costs.

➢ *Unifying Methodology for EPC/SPC* The instructor should warn of the problems associated with the use of autocorrelated data in the CPI in preparing control charts—namely, that numerous false signals are likely to result. The procedure for massaging the autocorrelated data to make them amenable to statistical monitoring should be discussed.

➢ *Fault Diagnosis* The last item concerns what to do when the presence of assignable causes is detected. Expert systems are being used in some applications to deduce what actions to take when an assignable cause is detected. Again, due to time limitations, only an introduction to expert systems can be given here.

A study of the foregoing topics, together with the standard material currently covered, would lead to a more effective process control course.

While we have essentially focused on single-loop systems in this paper, the ideas can be extended to multivariable systems as well. A suitable (multivariable) controller would be needed, however, in order to maintain each quality variable of the multivariable system within specified limits. The discussion on statistical monitoring would remain unchanged.

## CONCLUSIONS

We have offered some comments on the undergraduate process control course and have shown how the unifying methodology for engineering and statistical process control brings attention to the topics that should be studied to gain a fundamental understanding of engineering process control from a quality control perspective. We hope that the material presented here will be helpful to other process control instructors.

## NOMENCLATURE

- a normally distributed random variable
- C controlled variable
- E error (set point - measured value)
- $E_t$ forecast error, $C_t - \hat{C}_t(t-1)$
- F delay expressed as number of integer sampling periods
- G transfer function
- K gain
- k $k^{th}$ sampling instant
- L load
- M manipulated variable
- N noise
- R set point
- s Laplace transform operator
- z z-transform operator

### Subscripts

- c pertaining to controller
- D pertaining to derivative mode in Eq. (1)
- I pertaining to integral mode
- L pertaining to load
- P pertaining to process
- t pertaining to time
- ^ estimated value

### Greek

- $\theta(z^{-1})$ polynomial in $z^{-1}$
- $\phi(z^{-1})$ polynomial in $z^{-1}$
- $\delta(z^{-1})$ polynomial in $z^{-1}$
- $\omega(z^{-1})$ polynomial in $z^{-1}$
- $\phi_p$ autoregressive polynomial of order P, $\left(1+\phi_1 z^{-1}+\phi_2 z^{-2}+\ldots+\phi_p z^{-p}\right)$
- $\theta_q$ moving average polynomial of order q, $\left(1+\theta_1 z^{-1}+\theta_2 z^{-2}+\ldots+\theta_q z^{-q}\right)$
- $\varepsilon_t$ prediction error, $C_t - \hat{C}_t$
- $\nabla$ backward difference operator $(1 - z^{-1})$
- $\sigma$ standard deviation
- $\theta$ dead-time
- $\tau$ characteristic time constant
- $\zeta$ damping coefficient

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# TEACHING TEACHERS TO TEACH

## *The Case for Mentoring*

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Teaching—like medicine, auto mechanics, professional basketball, and chemical engineering—is a craft. There are distinct skills associated with its practice, which people are not born knowing. Some people are naturals (in education, the so-called "born teachers") and seem to develop the skills by intuition; most are not, however, and need years of training before they can function at a professional level. Doctors, mechanics, basketball players, engineers, and teachers at the K-12 level routinely get such training—but not college professors, most of whom get their PhDs, join a faculty, and set off to teach their first course without so much as five seconds on how one does that.

Not realizing that there are alternatives, new professors tend to default to the relatively ineffective teaching methods they experienced as students. Although they work hard to make the course material as comprehensible and interesting as they can, many of them consistently see only glazed or closed eyes during their lectures, terrible test grades, and evaluations suggesting that the students liked neither the course nor them. Some of them eventually figure out better ways to do their job; others never do and spend their careers teaching ineffectively.

The absence of college teacher training is not an unrecognized problem, and at least some institutions are trying to address it. Various schools offer graduate courses on teaching, hold faculty teaching workshops lasting anywhere from one morning to several days, and provide teaching consultants to critique end-of-course evaluations and videotaped lectures. Although such programs are worthwhile and should be standard on every campus, there are limits to what they can accomplish. You can't turn someone into a skilled professional in a one-semester course, much less in a three-day workshop or a two-hour consultation. True skill development occurs only through repeated practice and feedback.

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Fortunately, the resources needed for effective training of college teachers are readily available on every campus. Most academic departments have one or more professors acknowledged to be outstanding teachers by both their peers and their students. They have learned how to put together lectures that are both rigorous and stimulating and homework assignments and tests that are comprehensive, challenging, instructive, and fair. They have found ways to motivate students to want to learn, to co-opt them into becoming active participants in the learning process, to help them develop critical and creative thinking and problem-solving abilities.

Unfortunately, under our present system, faculty members may collaborate on research but generally don't even talk to each other about teaching. Most professors must therefore plod through the same lengthy trial-and-error process when learning how to teach, seldom benefitting from the knowledge and experience of their colleagues.

Here is a proposal for what I believe might be a better way.

- *All new professors should team-teach their first two courses with colleagues who have earned recognition as excellent teachers and who agree to function as mentors.*
- *The first course would begin with the mentor taking most of the responsibility for laying out the syllabus and instructional objectives, planning and conducting the class sessions, and constructing the homework assignments and tests. Both professors would attend most classes and have regular debriefing sessions to go over what went well, what didn't go so well and why, and what to do next. The protégé would gradually take over more of the course direction, ending up with primary responsibility by the end of the course.*
- *In the second course, the protégé would take sole responsibility for planning and delivering the course. The mentor (who may be the mentor from the previous semester or a different professor) would function entirely as a consultant, observing class sessions and participating in debriefing meetings.*
- *When planning teaching assignments, the department head should recognize that team-teaching a course and serving as a mentor to a new instructor is a heavier time burden than simply teaching a course alone, and should provide a suitable reduction in the mentor's other responsibilities. Ideally, the mentor would get additional compensation, such as a summer stipend, release time, or a travel grant.*

The potential benefits of this plan are evident. New professors would get a jump-start on learning their craft rather than having to rely entirely on painfully slow self-teaching. The experience would likely energize the mentors as well, stimulating them to reexamine and improve their own teaching as they provide active guidance to their junior colleagues. The overall quality of the department's instructional program would inevitably improve.

Caution, however—mentoring is also a craft, with its own assortment of skills and pitfalls. As it happens, teacher educators have explored this subject for decades and have developed a variety of methods to make mentoring successful.* If you find yourself serving as a mentor, formally or informally, consider the following guidelines:

- *When you teach, you often do subtle things that you learned by experience, and you also occasionally make errors in judgment when handling classroom situations. The inexperienced observing protégé is likely to miss it all. Go over items in both categories during debriefings.*
- *When protégés get into trouble in class, fight off the temptation to rescue them immediately. Instead, prompt them in debriefings to figure out for themselves what went wrong and how to fix it.*
- *Offer suggestions, not prescriptions. What you lay out for protégés explicitly is unlikely to stick. What they discover for themselves with your help, they will own.*
- *Don't try to turn your protégés into clones of you. Instead, help them find the teaching style best suited to their own strengths and personalities and encourage them to develop and perfect that style.*

Only one step remains to complete the process. When a department colleague—perhaps one of your protégés—starts to win teaching awards, talk her into serving as a mentor for the next faculty hire. When she protests that she doesn't know how, pass along this column and add that while she's figuring it out you'll be happy to be her mentor. ❐

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* *I am indebted to Dr. Rebecca Brent, my mentor on all matters related to teacher education, for many of the ideas that follow. See also T.M. Bey and C.T. Holmes,* Mentoring: Contemporary Principles and Issues, *Reston, VA, Ass'n. of Teacher Educators (1992)*

***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.***

# WHEN IS A THEORETICAL STAGE NOT ALWAYS A THEORETICAL STAGE?

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The study of continuous distillation is one of the cornerstones of an undergraduate course in chemical engineering. Indeed, the presentation of the McCabe-Thiele construction is a well-rehearsed routine. Therefore an exercise which makes more experienced undergraduates reconsider widely used textbook asumptions and, in addition, to think more broadly about the subject is very useful.

## BACKGROUND

The McCabe-Thiele analysis starts with a diagram much as the one shown in Figure 1.[1-4] The reboiler of Figure 1 must be a kettle (see Figure 2) in order to phase-separate vapor and liquid and meet the requirement that vapor return and bottoms be in equilibrium. Indeed, some undergraduate textbooks provide this detail.[5-7]

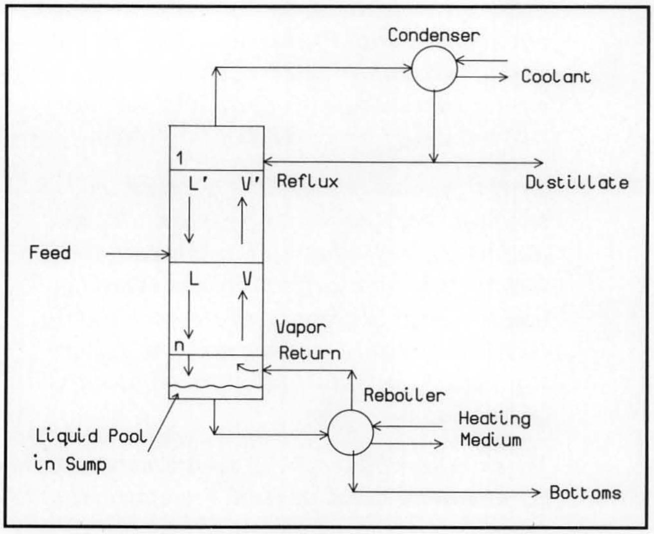


*Figure 1*

Kettle reboilers, however, are not widely used because they have some significant disadvantages. The most commonly cited disadvantages are:[8,9]

- The high cost of the large shell to permit vapor-liquid phase separation and provide bottoms surge volume.
- Their tendency to collect dirt and to foul.
- A liquid pool submerging the reboiler tubes, to a first approximation, operates uniformly at the bottoms composition and hence boils at the highest temperature; this narrows the temperature driving force and leads to increased heat transfer area.

It is important to note that kettle designs permit high vaporizations—up to 80% of the liquid from the bottom tray of the column. Columns can

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thus be designed with liquid/vapor traffic ratios as low as 1.25.

Thermosyphon reboilers are much more commonly used. They may be either vertical units with vaporization inside the tubes, or horizontal units with vaporization inside the shell. Thermosyphon designs rely on a head of liquid (achieved by precise positioning of the reboiler relative to the column) and careful piping design to force the return of a two-phase mixture to the column. Thermosyphons are popular because:[8,9]

- Their design normally allows for a high process flowrate through the unit; this is beneficial in reducing fouling and promoting a high heat transfer coefficient.
- Both phase separation and surge volume are moved to the column sump, where these functions are more easily managed.
- Boiling occurs over a range of temperatures, and hence there is an improved driving force for heat transfer.
- A cheaper overall construction is obtained because of the above factors.

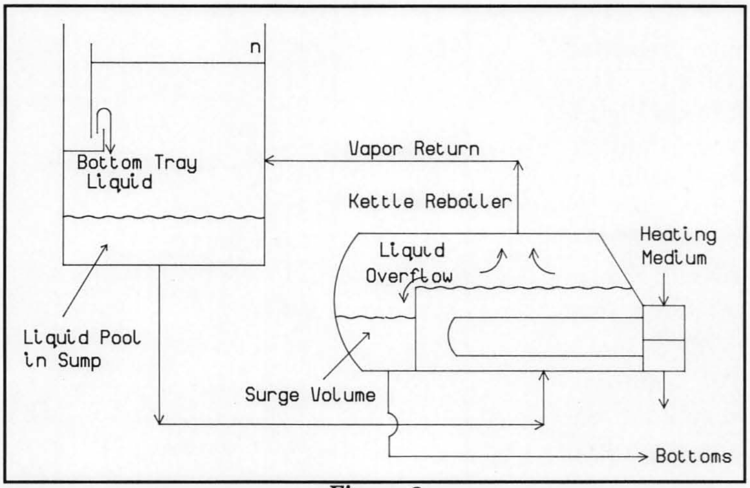


*Figure 2*

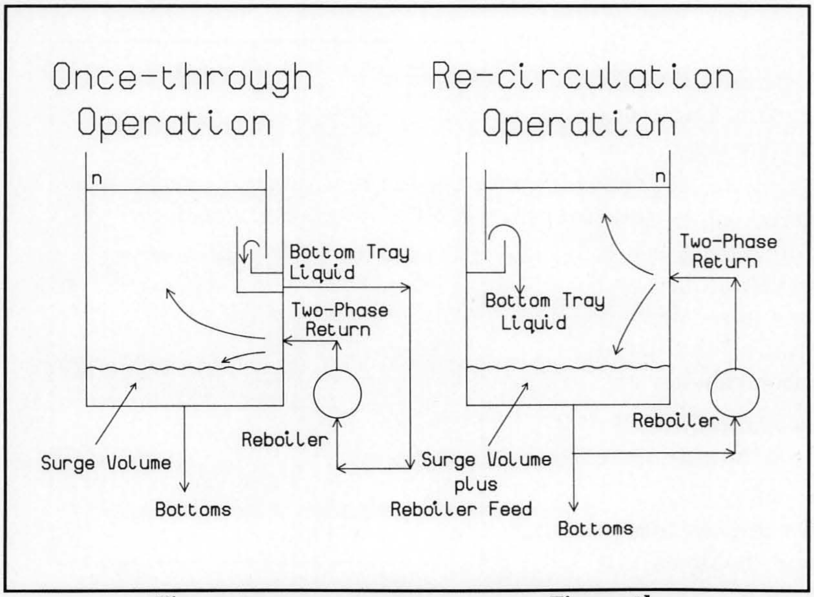


*Figure 3a* *Figure 3b*

One particular feature of thermosyphon design is a strict upper limit on the per-pass vaporization achievable, normally about 25% of the process liquid entering the unit with vaporization in the range of 5-15% being normal. Indeed, a high percentage of liquid in the two-phase return is an advantage because it ensures that the reboiler tubes are kept "wet," thus improving heat transfer and minimizing fouling. If a thermosyphon is connected to a column in an arrangement analogous to that for a kettle (contributing one theoretical stage with exiting vapor and liquid in equilibrium), then Figure 3a applies. But the upper limit on per-pass vaporization now poses a severe difficulty for the distillation design because liquid/vapor traffic ratios below 4.0 are not possible. Hence, once-through operation is only generally suitable for reboiled strippers.

Far more flexibility is achieved by recirculation operation (see Figure 3b). Now a low liquid/vapor traffic ratio can be achieved in the column because the process flowrate through the reboiler is boosted by recirculation of part of the returning liquid, keeping the per-pass vaporization to acceptable levels. There are two disadvantages, however:

1. The vapor rising from the reboiler toward the bottom tray is *not* in equilibrium with the bottoms liquid. Hence, the recirculation reboiler has a separation performance that is equivalent to less than one theoretical stage (this answers the question posed in the title of this article).
2. A portion of the bottoms liquid will experience a long residence time in the column sump, resulting in repeated contact with the hot tube surfaces of the reboiler—this may promote fouling.

Despite these disadvantages, recirculating reboilers are widely used, and adapting the McCabe-Thiele construction is a challenging exercise for more experienced undergraduates.

This exercise is useful, not only because it brings real industrial practice to the students' attention (often significantly different from the theory presented in textbooks), but also because it may be widened to include discussion of other aspects, such as

- Kettle versus thermosyphon reboilers
- Vertical versus horizontal thermosyphons
- Exchanger cleaning
- Thermosyphon operation
- Distillation column elevation
- Space requirements for different reboilers
- Detailed design of distillation column internals

This article concentrates on the McCabe-Thiele construction. Normally, it is helpful for the instructor to summarize some of the discussion contained in the "background" section above before students commence with the following "problem."

## Problem Statement

The McCabe-Thiele construction for distillation is presented as taking credit for one theoretical stage in the reboiler. This is based on the traditional use of a kettle reboiler (see Figure 2). Industrial practice is often different, however, and involves using either a once-through or a recirculation thermosyphon (see Figure 3).

**(a)** Which of the two reboiler arrangements shown in Figure 3 is not equivalent to a theoretical stage? Give your reasons.

**(b)** The flows and more volatile component (MVC) compositions in the bottom section of a distillation column featuring a recirculation thermosyphon are shown in Figure 4. Derive the equation

$$x_b = \frac{Lx_n + (R - V)x_r}{(L + R - V)} \tag{1}$$

and use the result to assist sketching recirculation reboiler operation on a McCabe-Thiele diagram. Comment on the asymptotic behaviour when R is very large compared to L and V, and when R = V.

**(c)** A two-component mixture, having relative volatility of 2.0, is distilled to produce a bottom product with $x_b = 0.1$. If the liquid/vapor traffic ratio below the feed is 1.5, and 15% of the reboiler feed is vaporized per pass, draw a detailed McCabe-Thiele construction (making the usual simplifying assumption) for the recirculation reboiler and bottom tray.

**(d)** Express the separation performance as a liquid-phase Murphree efficiency.

**(e)** Devise column sump internals which give the advantage of recirculation but ensure that the reboiler behaves as a theoretical stage.

## Solution

**(a)** The arrangement of Figure 3b is not equivalent to a theoretical stage as explained in the "background" section.

**(b)** Equation (1) is very simply derived as a MVC mass-balance around the column sump and may be interpreted as expressing bottom product composition as a blend of bottom tray liquid and reboiler return liquid. Figure 5 shows the required McCabe-Thiele construction where recirculation operation is represented as a partial step (rather like the construction taking into account tray efficiency) between operating and equilib-

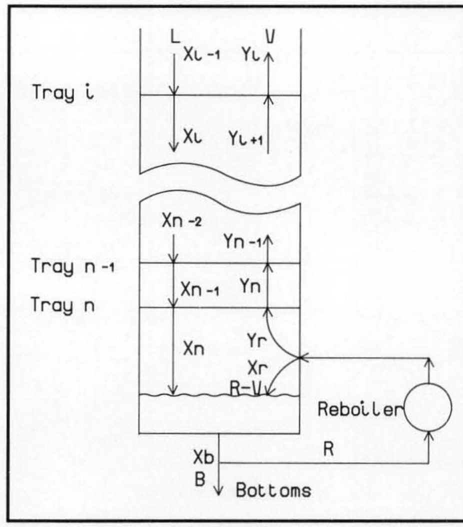


*Figure 4*

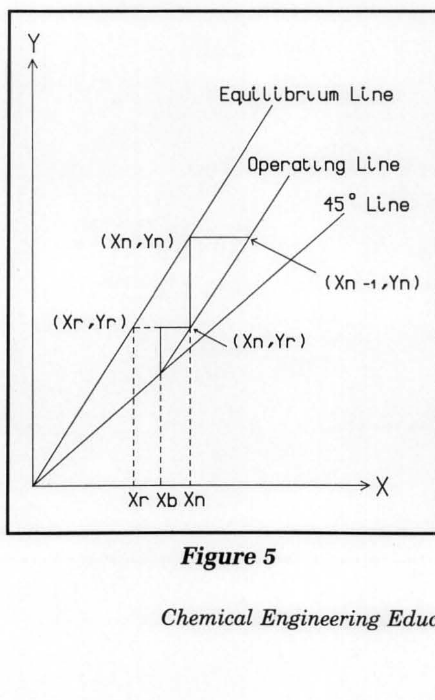


*Figure 5*

rium lines. Point $(x_n, y_r)$ must lie on the operating line, and $(x_r, y_r)$ on the equilibrium line; $x_b$ lies between them in accordance with Eq. (1) and controls the step size.

When R is very large compared to L and V, then $x_b$ approximates $x_r$ and the system behaves as a theoretical stage.

When R = V (*i.e.*, the minimum reboiler feedrate), then $x_b$ equals $x_n$ and no separation is achieved.

**(c)** The general equation for the operating line, using the symbols of Figure 4, is

$$y_{i+1} = \frac{L}{V} x_i - \frac{B}{V} x_b \tag{2}$$

Equation (2) may be applied at any elevation below the feed. Hence

$$y_r = \frac{L}{V} x_n - \frac{B}{V} x_b \tag{3}$$

The reboiler return comprises vapour and liquid in equilibrium. Hence $y_r$ and $x_r$ are related by

$$y_r = \frac{\alpha x_r}{1+(\alpha-1)x_r} \tag{4}$$

Recirculating systems have an additional degree of freedom—namely the process flowrate, R, through the reboiler—and it is this variable that

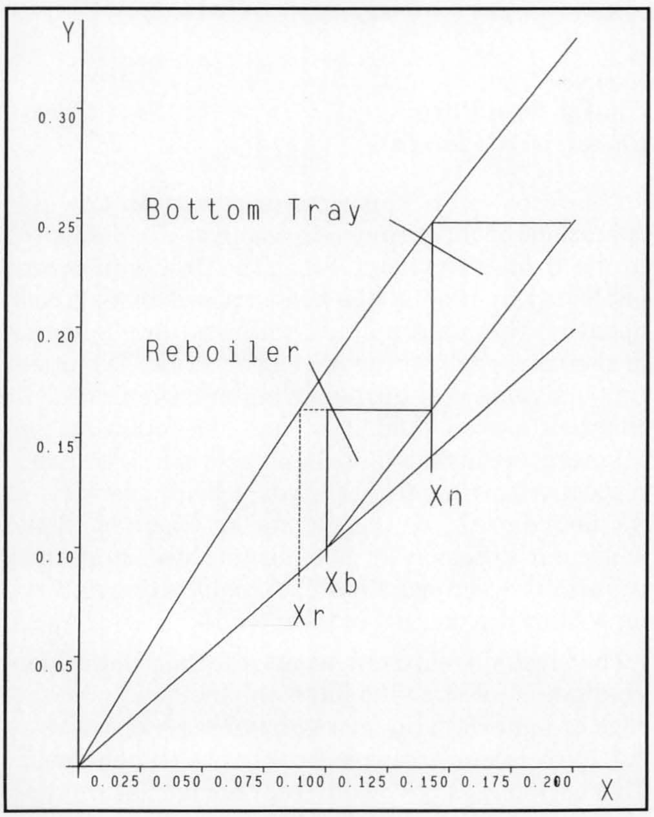


***Figure 6***

fixes the size of the partial step. An extra equation is required for the analysis, and it is obtained by a MVC mass-balance around the reboiler

$$Rx_b = (R-V)x_r + Vy_r \tag{5}$$

or

$$x_b = (1-f)x_r + fy_r \tag{6}$$

where the reboiler fraction vaporization, f = V/R, is a design parameter.

To perform the construction, $x_b$ is known, but three compositions $(x_n, x_r, y_r)$ are unknown. There are three equations in these unknowns, however—namely Eqs. (3), (4), and (6). Using the data in the Problem Statement,

$$\frac{L}{V} = 1.5, \quad \text{so} \quad \frac{B}{V} = 0.5, \quad \text{and} \quad f = 0.15$$

we obtain

$$y_r = 1.5\, x_n - 0.05 \tag{7}$$

$$y_r = \frac{2x_r}{1+x_r} \tag{8}$$

$$0.1 = 0.85\, x_r + 0.15\, y_r \tag{9}$$

Eliminating $y_r$ between Eqs. (8) and (9) gives a quadratic in $x_r$ having feasible solution $x_r$ = 0.08885. Figure 6 shows the completed construction where $y_r$ = 0.1632 and $x_n$ = 0.142.

**(d)** The normal convention is to express stage mass transfer efficiency in terms of vapor composition change. In this instance, however, there is no vapor feed to the stage, and the efficiency must be expressed in terms of liquid composition change,

$$E = \left(\frac{x_n - x_b}{x_n - x_r}\right) \times 100 = \left(\frac{0.142-0.1}{0.142-0.08885}\right) \times 100 = 79\% \tag{10}$$

Alternatively, if Eq. (1) is subtracted from $x_n = x_n$, the efficiency of the reboiler can be shown to be

$$\frac{E}{100} = \frac{R-V}{L+R-V} \tag{11}$$

Thus, knowing that L/V = 1.5 and V/R = 0.15, then L/R = 0.225, and we again obtain E = 79%. Equation (11) would be useful if the equilibrium data is not expressed in a simple form permitting analytical solution. Trial-and-error solution could be used to find $x_r$ and $x_n$ such that the predetermined efficiency is obtained.

**(e)** This part is a challenging exercise for students, since the problem is at two levels: first, finding a philosophy, and second, devising equipment

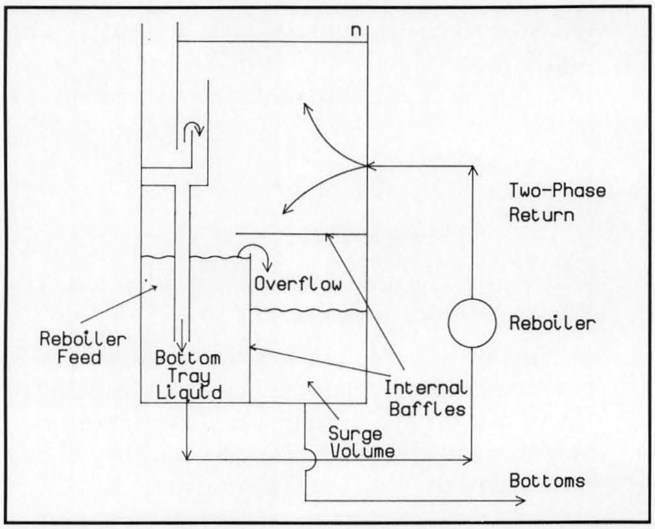


*Figure 7*

to implement the philosophy. In summary, the philosophy is to preferentially route the bottom tray liquid to the reboiler and sufficient reboiler return liquid to the bottoms. Excess reboiler return liquid (not needed as bottoms) joins the bottom tray liquid as reboiler feed. One way of implementing this on larger diameter columns is illustrated in Figure 7; note that the down-pipe from the trap-out mixes the bottom tray liquid into the excess reboiler return liquid well below the overflow level—this ensures the overflow is predominantly reboiler return liquid. With this type of design, the vapor return and bottoms are in equilibrium so the system acts as one theoretical stage.

## INDUSTRIAL PRACTICE

The loss of part of a theoretical stage is widely recognized in industry, but response varies considerably. At one extreme some companies do not take credit for the separation due to the reboiler (treating it as a safety factor) unless it is a kettle when full credit is taken for one theoretical stage. At the other extreme, others simply count the reboiler (irrespective of type) as one theoretical stage—but then a conservative tray efficiency applied to the column hides any shortcoming. Based on the approach in this article, it seems that a recirculating reboiler generally has a separation efficiency of at least 60%. Hence, even though one might not wish to actually perform the construction as described, it would be quite safe to credit the reboiler with a separation equivalent to an efficiency of 50%.

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**ChE** ***book review***

# *CHEMICAL ENGINEERING: Vol. 1. Fluid Flow, Heat Transfer and Mass Transfer*

by J.M. Coulson and J.F. Richardson, with J.R. Backhurst and J.H. Harker

*Pergamon Press, Headington Hill Hall, Oxford, OX3 0BW, United Kingdom; $48 (paperback) (1990)*


***Reviewed by***
**Chang-Won Park**
***University of Florida***


This book is an undergraduate text on the unit operations of chemical engineering and is published in the United Kingdom. Since the first edition was published in 1954 it has been revised three times, updating the material as significant developments in chemical engineering have been made. The material is divided into thirteen chapters: the first eight chapters are on fluid flow, and the following two chapters are devoted to heat and mass transfer, respectively; Chapter 11 gives a brief overview of the boundary layer theory, and in Chapter 12 the molecular diffusion in momentum, heat, and mass transfer is described; finally, humidification and water cooling are treated in Chapter 13.

The level of treatment seems adequate for undergraduate students who have an elementary knowledge of material and energy balances but who may not have taken a course in transport phenomena. This book uses slightly different nomenclature than textbooks published in the U.S., but not to an extent that will cause a serious problem. Compared to *Unit Operations of Chemical Engineering* (4th edition), by McCabe, Smith, and Harriott (which may be the most widely used textbook in the U.S. on the subject), this book contains more example problems, more figures, and more pictures (especially for the section on fluid flow), which may be an important feature for a textbook. It also contains more detailed design aspects of pumps, flow meters, heat exchangers, etc.

Units and dimensions are briefly covered in Chapter 1, followed by elementary thermodynamic principles in Chapter 2. Chapter 3 describes the flow in pipes and channels, including an adequate level of description for non-Newtonian behaviors. The flow of compressible fluids is described in Chapter 4. Starting with the flow of gas through a nozzle or orifice, the unique features of compressible fluid flow are well enough described so that students can comprehend the subject matter without too much difficulty. Multiphase flow, which is important in many areas of chemical engineering but which is a difficult subject to handle at the undergraduate level, is treated in Chapter 5. The empirical developments of liquid-gas and fluid-solid systems are described, including up-to-date literature references. Chapters 6, 7, and 8 describe flow measurements, liquid mixing, and pumping of fluids, respectively.

Chapter 9 is devoted to heat transfer. This long chapter covers the fundamentals of conduction, convection, and radiation as well as heat transfer involving a phase change and heat exchangers. The material and the level of treatment are similar to those of many other undergraduate textbooks. Finally, mass transfer is treated in Chapter 10. However, only the fundamentals of mass transfer are described in this volume—the various mass transfer processes such as distillation, liquid-liquid extraction, and gas absorption are covered in Volume 2 of the Chemical Engineering Series, *Particle Technology and Separation Processes.* The flow past immersed bodies, including fluidized beds and packed beds, is also covered in Volume 2.

In summary, this volume can serve as an excellent textbook or a principal reference for an unit operations course on fluid flow and heat transfer. Chapters 1 through 9 constitute an adequate amount of material to be covered in one semester, and the many example and homework problems contained in this volume are a useful feature. The treatment of mass transfer, however, is rather brief and a separate volume must be used if a course is to be devoted to mass transfer operations. ❒

## ChE book review

### *CHEMICAL ENGINEERING: Vol. 2. Particle Technology and Separation Processes, 4th ed.*

**by J.M. Coulson, J.F. Richardson, J.R. Backhurst, and J.H. Harker**

*Pergamon Press, Headington Hill Hall, Oxford, OX3 0BW, United Kingdom; 968 pgs, $51 (paperback) (1991)*

***Reviewed by***
**Benjamin J. McCoy**
**University of California, Davis**

This book, nearly 1000 pages in length and weighing over four pounds, is a bargain at $51.00. Part of a six-volume introduction to chemical engineering, this particular volume covers separation and particle processes. The rule-of-thumb that any book in its 4th edition is worth knowing applies in this case. The authors have prepared a carefully written and judiciously planned book which is rewarding to read and study. Material from the 3rd edition has been revised, reordered, and rewritten, and new chapters have been added on adsorption, ion exchange, and chromatographic and membrane separations.

With the need for chemical engineering to expand beyond its traditional central role in the petrochemical industries, this book provides a satisfactory background for the particle and separation technologies important to biotechnology, biomedical applications, materials science, and environmental engineering. It will serve nicely as either a handbook on the shelf of the practicing chemical engineer or the teacher of chemical engineering, or as a textbook used in a course on separations and applied mass transfer. The prerequisite courses are introductory physics, chemistry, and calculus. The book has an adequate supply of homework problems and an abundance of cited references for the researcher.

The authors have maintained a commendable balance of practical engineering and mathematical fundamentals. Necessary for application to industrial applications, the book is well stocked with photographs, diagrams, and explanations of equipment. The book supplements the now-usual mass, momentum, and energy transport phenomena approach and includes thermodynamics of adsorption, physics of particles, and dynamics of chromatography. Treating the essential physical processes, the authors present concise derivations of mathematical relationships that succinctly capture the significant, basic quantitative concepts.

*Continued on page 199.*

# A COMPREHENSIVE PROCESS CONTROL LABORATORY COURSE

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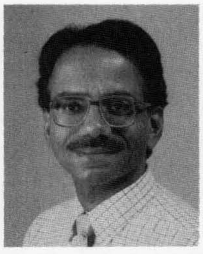
Process Control and Simulation is a 4-credit course in the department of chemical engineering at the University of New Hampshire. Classroom lectures (three hours per week) are supplemented with a two-and-a-half hour laboratory session held once a week. The course is traditionally taught in the spring semester of the senior year. The topics include, but are not limited to, dynamic behavior of chemical engineering processes described by differential equations, feedback control concepts and techniques, stability analysis, and advanced control techniques.

Students are usually divided into groups of two or three, and each group is required to do six different experiments over the course of the semester. These experiments are designed to expose the students to the practical aspects of almost all the theoretical topics covered in class. The basic materials and equipment are supplied for all the experiments. The students have to assist in designing and building the experiments, decide *a priori* what data they want to collect, perform the experiments, analyze the data, and submit a report. Some of the experiments are designed to permit flexibility in terms of simulating various process configurations (first order, second order, third order) or to demonstrate various process control principles discussed in class. The important features of each experiment will be highlighted in the following paragraphs.



***P.T. Vasudevan** is a chemical engineering faculty member at the University of New Hampshire. He obtained his PhD from Clarkson University. His research interests are in the area of catalysis and biocatalysis.*



The six experiments are divided into two phases. The first three experiments (phase one) are performed by all the students prior to the spring break, while the remaining three experiments (phase two) are performed after the spring recess.

## EXPERIMENTS

Two of the three experiments in the first phase deal with determination of time constants of simple processes such as liquid level in a tank or pressure in an air cylinder. The liquid-level process consists of three Plexiglass tanks with interconnecting valves. Water can be pumped to any of the three tanks, and the feed water pressure is maintained constant to avoid any fluctuations in the flow rate. The control valve is located on the feed line. The students are at liberty to select one, two, or all three tanks and set the system up as either an interacting or a noninteracting process. The level is monitored in the third tank by means of a pressure transducer mounted at a height of six inches above the tank bottom, and the signal from the transducer is then sent to a PC equipped with data-acquisition capabilities (in this case, a Metrabyte DAS-8 card). Labtech Notebook is used to set up the various input and output channels. The PC is equipped with additional Metrabyte boards for process control. The students are thus exposed to various features of data acquisition and control, and instrumentation hardware very early in the semester.

In order to determine the time constant of the process, the students have to use both a pulse- and a step-forcing function. These forcing functions are set up in an external file (in ASCII) and can be accessed by Labtech Notebook when needed. Thus, data pertaining to the magnitude of the step or pulse and the type of pulse are stored in this external file.

The controller (output channel) in open loop reads the information from this file and changes the output to the control valve accordingly. The duration of the pulse or the exact moment at which the step change is to be introduced is controlled by adjusting the sampling rate in the output channel. The entire operation is therefore carried out in a precise fashion, with very little human intervention.

The data are recorded in a file and are also continuously monitored on the VGA monitor, so the students can compare the experimentally obtained value for time constant with the theoretical value (knowing the valve resistance and area of the tank). A linear valve is used in the experiment, and the valve resistance can be easily determined experimentally. The determination of time constant for a step-forcing function is straightforward. For the case of a pulse-forcing function, the following method is used for determining the time constant for a first order process (single tank).

We let

R = linear valve resistance

H = magnitude of the pulse

T = duration of the pulse

$h_d(s)$ = height in the tank in terms of deviation variables

Then, in the Laplace domain

$$h_d(s) = \frac{RH}{\tau s+1}\left(\frac{1-e^{-sT}}{s}\right) \tag{1}$$

In the time domain, for $t > T$,

$$h_d(t) = RH\left(e^{-(t-T)/\tau} - e^{-t/\tau}\right) \tag{2}$$

We now define a function, f, equal to the product of $h_d(t)$ and time, t. A plot of f versus time t will go through a maximum. By differentiating Eq. (2) with respect to time and equating it to zero, we can show that the maximum occurs when $t = \tau$. Thus, this method gives a simple procedure for estimating the time constant for a first-order process. Alternately, a plot of $\ell n\ h_d(t)$ vs. time is a straight line with a slope equal to the reciprocal of $\tau$. However, Eq. (2) does not take into consideration the response of the process for values of $t < T$. If the duration of the pulse is sufficiently long, it is necessary to consider the complete solution.

This problem is easily solved in the following manner. It is possible to delay the storage of information by specifying a time delay equal to the duration of the pulse, T. By setting up a "calculated channel" it is therefore possible to monitor and store time in an external file as (t - T), (referred to hereafter as "adjusted time"). In the next channel, the data are stored or displayed as the product of height (in deviation variables, also easily set up in notebook through the use of "calculated channels" once the initial steady-state height is known), and adjusted time. The product of height and adjusted time (function f) versus the adjusted time is continuously displayed on the screen (and also stored in an external file) so that the information can be plotted later on.

Such a plot is shown in Figure 1. (Since the sampling rate is 1 Hz, the data points are not shown.) From this plot the time constant can be determined as the value on the abscissa corresponding to the value on the ordinate where the function f goes through a maximum. Or, to obtain an accurate estimate, a differential analysis of the data (function f with respect to time) can be performed.

The value of the time constant from the plot is about 210 seconds. This compares very well (within 5%) with the value of time constant obtained using a step change. For this particular experiment, the duration of the pulse was 100 seconds and the magnitude of the pulse (change in flow rate) was 0.32 $ft^3$/min. It is interesting to note that the valve resistance can easily be determined once the time constant for the process is known. Setting t = t is Eq. (2), we get

$$h_d(\tau) = \frac{f}{\tau} = 0.368\, RH\left(e^{T/\tau} - 1\right)$$

The only unknown in this equation is R, and it can be determined.

The same experimental setup is used to introduce concepts such as transmitter gain and dead time. For instance, since a pressure transducer is used to measure the height in the tank or the pressure in the cylinder (in the air-pressure process experiment), the students are required to calculate the

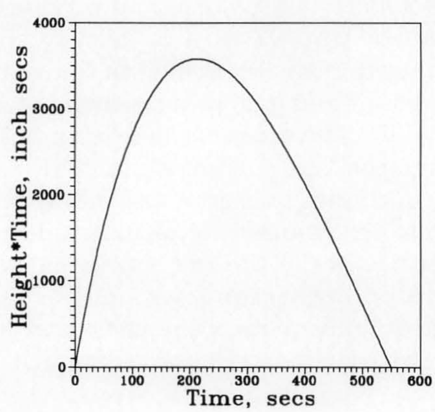



***Figure 1.*** *Determination of time constant from a pulse test. Sampling rate = 1 Hz*

transmitter gain. This information is then entered into the input channel. The students thus gain an understanding of how a transducer works and the range of the output signal for electrical and pneumatic transducers.

The first fifteen to twenty minutes of each laboratory period is spent in demonstrating the process-control principles discussed in class the previous week. For example, the liquid-level experiment is used to demonstrate types of controller action and how to set up the right action (reverse or direct) in the output channel. The PC is equipped with a Metrabyte DDA-06 controller card. The phenomenon of reset windup and the concept of stability are also demonstrated soon after the theoretical material is presented in class. Since Labtech Notebook uses the position form of the controller equation, reset windup is demonstrated very effectively.

The students also develop a good understanding of the dynamics of PID control and the effect each element (P, I, D) has on the overall control process. Important concepts such as offset, or how a simple first-order process with PI control can behave in an oscillatory manner, or how a second-order overdamped process with simple proportional control can become underdamped, are demonstrated with ease.

The pressure experiment is similar to the liquid-level experiment. Students are required to determine both the experimental and the theoretical time constants and to compare the two. They must determine the transmitter gain (scale factor) and offset and set up various channels in the Notebook.

The third experiment deals with control-valve calibration for both liquid and gas service. Here the students gain a practical understanding of concepts such as inherent and installed characteristics, valve coefficient, and valve flow characteristics. Once again, Notebook is used to set up various channels. A Metrabyte DAC-02 card is used to change the signal to the transducers located on the control valves for both liquid and gas, in increments of 1V (range is -5 to +5V). The students take data of flow rate, valve stem position, current signal to transducer (4-20 mA), upstream pressure, and downstream pressure. They are required to calculate and report the valve coefficients of the two valves as well as the type of valve (linear, equal percentage, quick opening) from suitable plots of the valve characteristics. In their report, the students are required to comment on the phenomenon of hysterisis observed in a plot of valve coefficient versus valve stem position.

The second phase of the laboratory deals with controller tuning based on Ziegler-Nichols closed-loop settings, Cohen-Coon open-loop tuning setting, or data from a pulse test. The liquid-level experimental setup or the air-pressure process can be used again. In the case of the liquid-level experiment, the students can choose any configuration they like. From the process reaction curve generated (here again, Labtech Notebook is used to set up the channels and store the information), the students use Cohen-Coon setting to determine the controller settings. They select a controller (P, PI, or PID) and determine the response to both servo and load changes. The controller settings obtained from the process reaction curve serve as preliminary estimates, and the students are required to obtain the optimum settings using a dynamic criterion such as IAE, ISE, or ITAE. This is easily done through the use of various "calculated channels" of Notebook, and IAE, ISE, and ITAE are set up in different channels.

The display window for the monitor is divided into four sections, and the students can observe the actual height in the tank, the error, IAE, ISE, or ITAE. They are required to select one of the integral criteria and try to obtain the optimum controller settings. This is done by keeping the reset time constant, for instance, and changing the proportional gain and determining the response to a unit step change in the set point (always from the same value). The students then change the integral time (keeping the gain constant) and observe the response. In each case the integral value is reported.

The second experiment also deals with controller tuning. This is done using the Ziegler-Nichols closed-loop tuning method. The second half of this experiment consists of using a pulse test to generate a Bode plot. The objective of the experiment is to determine the open-loop transfer function and calculate the overall gain, time constant, and dead time, if any. The students have to decide on a proper pulse duration and magnitude.

The pulse is introduced by changing the position of the control valve, and hence the flow rate to the system, for a known duration. This is achieved by setting the output channel in "open loop," which in turn accesses an external file to obtain values of the controller output. Care is taken to ensure that the system returns to its original steady state. The input and output data are then Fourier-transformed and divided to give the system transfer function in the frequency domain, G(iw). From the amplitude ratio and phase angle, Bode plots are constructed and the various parameters determined. The calcu-

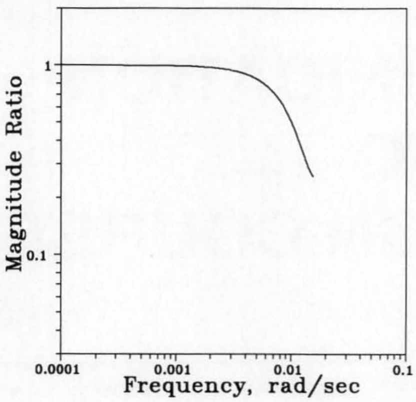



***Figure 2.*** *Bode plot generated from a pulse test: magnitude ratio versus frequency.*

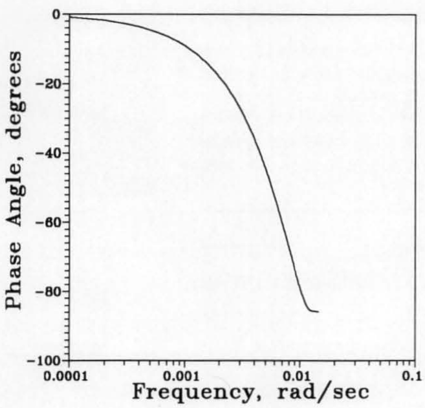



***Figure 3.*** *Bode plot generated from a pulse test: phase angle versus frequency.*

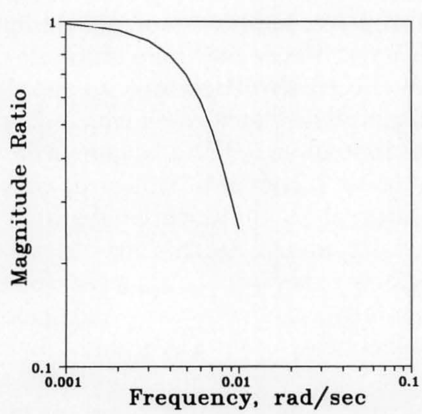



***Figure 4.*** *Bode plot generated from a pulse test: second-order system.*

lation of G(iw) from the pulse data is achieved by representing the transfer function as

$$G(iw) = \frac{\int_0^\infty y(t)\cos(wt)\,dt - i\int_0^\infty y(t)\sin(wt)\,dt}{\int_0^\infty x(t)\cos(wt)\,dt - i\int_0^\infty x(t)\sin(wt)\,dt}$$

where x(t) and y(t) are the input and output functions.

Then

$$G(iw) = \frac{(AC + BD) + i(AD - BC)}{C^2 + D^2}$$

where

$$A = \int_0^{T_y} y(t)\cos(wt)\,dt \qquad B = \int_0^{T_y} y(t)\sin(wt)\,dt$$

$$C = \int_0^{T_x} x(t)\cos(wt)\,dt \qquad D = \int_0^{T_x} x(t)\sin(wt)\,dt$$

The duration of the input pulse and the time it takes the response to return to the original steady state, are $T_x$ and $T_y$, respectively. The integrals are evaluated numerically by picking different values for the frequency, w. The students do this on a mainframe computer after up-loading the data from the PC to the mainframe. The experiment yields reasonably accurate frequency response curves. Numerical integration becomes a problem because of the oscillatory behavior of the sine and cosine terms at high values of frequency.

Since there is practically no human input necessary while performing this experiment, and because of the resolution and sampling rate used, data noise is not a problem. The Bode plots generated for a first-order liquid-level process are shown in Figures 2 and 3. The magnitude ratio and phase angle at higher values of frequency are not shown because of the problems associated with integration. Figure 3 indicates that the phase angle reaches an asymptotic value around -90°, which is indicative of a first-order system without dead time. It is also evident from Figure 2 that the transfer function of the system is exactly first order.

These observations are not surprising considering the fact that the process is first order and there is no measurement lag. The time constant for the process can be easily determined from Figure 2 once the corner frequency is known. The time constant is found to be about 200 seconds and is within 5% of the value previously reported.

The magnitude ratio for a second-order process (two interacting tanks) is shown in Figure 4. It is clear from the slope of the high-frequency asymptote that the system is exactly second order. Labtech Notebook also has a Fast Fourier Transform (FFT) capability that can be used to generate a power spectrum. In the above experiments, the students are also required to study the effect of sampling rate on data acquisition and on the control characteristics.

*Continued on page 193.*

# INTEGRATING COMMUNICATION TRAINING INTO LABORATORY AND DESIGN COURSES

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Recently, an increased awareness that good communication skills are essential in the engineering professions has led many chemical engineering departments to stress technical communication in the undergraduate curricula. In fact, a recent informal *Chemical Engineering Progress* survey[1] of the communication requirements in 156 U.S. and Canadian chemical engineering departments found that "with few exceptions, most of the departments that responded [to the survey] were placing greater emphasis on communication skills." As this survey indicates, chemical engineering departments take a variety of approaches to incorporating communication into the curriculum: some departments require a course in technical communication from another division of the university; others have developed courses which specifically emphasize technical communication within chemical engineering; while a third common approach is to integrate communication training into existing courses.

We initiated our communication program at the University of Illinois in 1989 by offering a junior-level communication-intensive course which emphasized the interrelationship between technical problem solving and communication of the results. Over the semester, the students completed several short technical projects and one longer one, each requiring some technical writing, revision, and oral work. Each project specified a particular audience and goal to be reached so that the students learned to structure their problem solving with the ultimate communication goal in mind. Limited to thirty students, the course provided individual attention and feedback, opportunities for discussion among students, writing workshops to help build composition skills, peer editing of both oral and written work, mock meetings and interviews to simulate professional experience, and an opportunity to view videotaped presentations for self-evaluation.

Encouraged by the success of this elective course, the department decided to extend practical writing and speaking experience to all students by stressing communication in the required senior-level laboratory and design courses, and we have continued to concentrate on this integrated program the past three years. Although students in the unit operations laboratory course and the design course always have been required to present their work through either written or oral reports, simply requiring communication work does not necessarily help students communicate more effectively. Therefore, to supply focused instruction and feedback, we have employed a communication instructor (CI) (someone from the English Department, hired for a two-thirds time position) to help integrate communication training into these senior-level courses. As this article will explain, through their experience in these two courses the students not only practice writing and speaking through a series of assignments evaluated for communicative ability and technical content, but they also receive instruction on technical communication, they learn to revise and edit their work as well as the work of their peers, and they gain experience in collaborative writing and speaking.

We have found that this integrative approach provides an opportunity for students to practice technical communication despite a tight curriculum which otherwise limited their communication work to a freshman rhetoric course. More importantly, though, it offers our students experience in writing and speaking within their own discipline.[2] Working on communication within a discipline provides students with professional experience and promotes learning through writing and speaking. Unlike technical communication courses where assignments may be artificially created for students to practice communicating, emphasizing communication in existing courses enables the students to use writing and speaking as tools for discovery. Research in the teaching of writing has also shown that students can learn material more fully through writing.[3] As C. W. Griffin points out, "We are beginning to realize that writing is not just the end product of learning; it is a process by which learning takes place."[4] Similarly, oral presentations can be approached as a learning tool. At Illinois, we are working to create opportunities for students to investigate and assimilate technical information through writing and speaking. When communication is approached as an integral part of the learning process, students start viewing it as an essential part of their work in engineering rather than as a chore which takes times away from learning technical material.

## DESCRIPTION: COMMUNICATION COMPONENT

### *Unit Operations Laboratory Course*

The communication component of the laboratory course includes instruction on writing and presenting experimental reports, a series of individual writing assignments, a revision exercise, and two oral presentations.

**Course Description** • Table 1 outlines the course requirements. The class is divided into lab sections of, at most, fifteen students. Each lab section is supervised by a graduate chemical engineering teaching assistant (TA) and meets in the lab for five hours per week. The oral presentations are held during the first hour of the lab period in a separate classroom, preferably equipped with an overhead projector. When the lab section is large (twelve to fifteen students), we divide the oral presentations into two rooms to save time. The professor and the TA then evaluate one set of talks each, and the CI rotates through the two rooms. Table 2 further outlines the required resources for the communication component in terms of teaching, space, and equipment.

**TABLE 1**
**Course Descriptions**

| Course | Enrollment | Group Size | Assignments | Written Reports* | Oral Presentations* |
|---|---|---|---|---|---|
| Unit Operations | 20-55 students | 3-4 students | 6 labs | 4 minor (3-5 pp.)<br>2 major (8-10 pp.)<br>1 revision of 1st major | 2 (15 minutes each) |
| Design | 20-55 students | 2-3 students | 1 design project | 2 preliminary (5 pp.)<br>1 final (20 pp.) | 2 (10 minutes each)<br>1 (20 minutes) |

**In the unit operations course the written and oral reports are prepared individually, whereas in the design course they are prepared in groups.*

**TABLE 2**
**Required Resources for Addition of Communication Instruction**

| Course | Teaching Resources | Classroom Space | Equipment | Salaries |
|---|---|---|---|---|
| Unit Operations (50 students) | • One professor<br>• One communication instructor<br>• One 25% time TA per 15 students | • One laboratory and two seminar rooms for oral presentations | • One overhead projector per seminar room | • $6,000/academic year for 33% time communication instructor |
| Design (50 students) | • One professor<br>• One communication instructor<br>• One 25% time TA per 15 students | One classroom and one seminar room for oral presentations | • Two overhead projectors<br>• Two videocameras<br>• One VCR for viewing videos | • $6,000/academic year for 33% time communication instructor |

All of the reports, including the revision, are graded for technical content by the TA or the professor, and the two major reports and the revision are graded by the CI as well. The oral presentations also are graded for both technical and communicative quality. In assessing the communicative quality for both written and oral reports, the CI emphasizes that successful expression of technical ideas requires more than good grammar skills or stylistic choices. Thus, the communication grades on the major reports and the revision are based primarily on the organization and use of the technical format; the writing style, grammar, spelling, and punctuation are checked but are not emphasized. The communication grade for the oral reports assesses the level of organization, the degree of preparation, and the presentation skills displayed. Altogether, the communication component comprises thirty percent of the grade for the course.

Throughout the semester the CI holds office hours, and students are encouraged to consult with the instructor individually, especially before revising their first major report. The CI also attends class and discusses how to prepare and organize written and oral reports, provides details on the technical format for written reports, and reviews stylistic concerns for technical writing. To provide further instruction on the technical format, the CI distributes a manual that details information about technical laboratory report writing. (This manual is written in the form of a technical report, so it provides an example of the technical-report format while also providing information about writing technical reports.)

**Analysis of the Communication Component** • Several attributes have contributed to the success of the communication component in the laboratory course. First, effective communication is approached as an integral and important part of the course. For some students, simply knowing that they will receive a communication grade encourages them to spend more time and effort in writing their reports and preparing their presentation.

Second, the course stresses that writing is a process rather than just a finished product to be evaluated. This approach is particularly emphasized through the revision exercise. After receiving substantial commentary from both the CI and the TA, the students are given two weeks to revise the report and resubmit it for technical and communication grades. The revision exercise gives the students a chance to apply feedback from written comments on their first draft, to recognize positive changes in their writing, and to learn how to improve their writing. In fact, in evaluating the revision process after the spring semester in 1992, ninety percent of the students surveyed noticed improvement in their second draft, half of them felt that their second draft showed "a lot" of improvement, and eighty percent indicated that the revision exercise helped them understand how to strengthen their writing.

An interesting student response to the revisions has been improved original drafts of the first major report. Many students are spending more time editing their first draft in an attempt to avoid significant revision. Ironically, these students are, in effect, completing multiple revision exercises. We find it encouraging to see students approach writing as a sequence of composing and editing stages since the editing and revision skills they are developing will undoubtedly prove useful to them in the future.

To incorporate further revision opportunities and to encourage individual contact with the CI during the writing process, we intend to hold office hours during the lab in a newly renovated Instructional Computer Lab (ICL) adjacent to the Unit Operations Laboratory. With lab sections scheduled for five hours and with, at most, twelve students per section, we can allot a portion of class time to writing conferences in the ICL, while the remainder of class time is spent taking data in the Unit Operations Lab.

### *Design Course*

The communication component of the design course complements the communication work in the laboratory course. In particular, the design course places more emphasis on oral work and provides experience in collaborative writing.

**Course Description** • Table 1 also describes the requirements for the design course. The students collaborate on the written and oral reports and receive group grades on all work completed. The written and oral reports receive both a technical and a communication grade, with the communication grade comprising thirty percent of the group grade for each report and presentation. The CI also provides instruction on writing and presentation techniques, distributes a manual on the technical format for design reports, and shows a video of an oral presentation from a previous semester. The first set of oral presentations are videotaped, and the students are required to view and evaluate their own presentations. When the class is large (fifty students), we divide the students into two rooms for the oral presentations, to save class time. The professor then grades one group for technical quality and communication, and the CI and the TA evaluate the second group. In addition, the students evaluate each other during the oral presentations, using a peer-evaluation form. Table 2 further outlines the required resources for the design course.

**Analysis of the Communication Component** • Several aspects of the communication work in the design course have proven successful. First, we have found it useful to provide samples of both written and oral assignments at the beginning of the course. The sample-report manuals, similar to the ones used in the lab course, are useful in helping students organize their reports. Over half of the students who seek individual help from the CI ask questions about organizing their report, and (especially in the design course) students often are unsure of what information to include and where to put it. Therefore, providing a standard to follow as a guideline has proven beneficial. Providing examples of professional design reports would also be useful, although we have not distributed such samples in the course thus far.

Similarly, the video shown at the beginning of the semester offers a more tangible guideline than can be explained in a lecture. This sample is not a "perfect" presentation (if one exists), but it demonstrates some good techniques to follow and some blunders to avoid when speaking. The video is shown after a lecture on preparing and organizing talks, and a discussion of the videotape follows its presentation. The video illustrates points introduced in the lecture (thereby setting a standard for class presentations), and the discussion gives students a lesson in peer evaluation. Throughout the remainder of the semester the students evaluate their classmates' oral presentations, using the form illustrated in Table 3. We purposely designed this form with only a few questions in order to give students more time to write comments. Even though peer evaluation is not a component of the grade, students have taken it seriously and have offered each other many helpful suggestions.

Videotaping the talks and requiring students to view and evaluate the videos has also been a successful exercise. For most students, especially those who have never seen themselves speak before, it is quite an eye-opener. Actually seeing their own difficulties and successes in speaking helps them identify areas which need improvement and gives them more confidence in their abilities. The students generally dislike watching themselves, but in the end admit that it was useful to them. Certainly, self-evaluation helps students prepare for their upcoming presentations; during the semesters when talks were videotaped and evaluated, the subsequent presentations showed great improvement.

Finally, the design course provides good experience in collaborative communication. Collaborative work, whether written or oral, has become increasingly common in the engineering professions. In the workplace, collaboration may involve working with others on research, or actually composing with others, or having others review and edit an already composed work, and the extent of collaboration varies according to the job and the specific group of people working together.[5] Thus, requiring students to collaborate on several stages of a large project—from planning to analysis and presentation—helps to develop essential organization, relational, and communication skills. A recent article on small-group interaction during writing projects noted that a well-written report "represents the team's successful working through of both small group and writing problems."[6]

Furthermore, collaboration teaches peer review. To aid the students, the CI discusses what to look for when editing others' writing and distributes a "Checklist for Collaborators."[7] (See Table 4.) According to a questionnaire distributed after the spring se-

**TABLE 3**
**Oral Presentation Evaluation Form**

**Speaker** ______________________________

*Place an X in the blank that represents your assessment of the category listed. Add some comments to explain your assessment. Then circle a number to represent an overall rating for the speaker. Write general comments at the bottom.*

| | Weak | | | | Strong |
|---|---|---|---|---|---|
| **1. Technical Content**<br>Relevance, clarity,<br>technical competence<br>**COMMENTS** | --------- | --------- | --------- | --------- | --------- |
| **2. Planning**<br>Organization,<br>transitions, continuity<br>**COMMENTS** | --------- | --------- | --------- | --------- | --------- |
| **3. Speaker's Manner**<br>Voice, eye contact,<br>gestures, confidence<br>**COMMENTS** | --------- | --------- | --------- | --------- | --------- |
| **4. Visual Aids**<br>Visibility, simplicity<br>appropriateness<br>**COMMENTS** | --------- | --------- | --------- | --------- | --------- |

**Overall Rating** (Circle) 1 2 3 4 5 6 7 8 9 10

**Comments:**

mester of 1992, when working in groups the students either split up the writing and then edited and proofread each other's sections, or they composed and revised together. Two-thirds of the respondents mentioned that they "revised," "edited," or "corrected" each other's work, indicating that they participated in peer review.

## DISCUSSION OF THE INTEGRATIVE APPROACH

Through our experiences over the past three years we have discovered other successes and difficulties of integrating communication work into existing engineering courses. Certainly, one distinct attribute of our program is the opportunity to work with students in two separate courses. Since most of the students take the lab and design courses in the fall and spring of their senior year, they have two sequential semesters of intense communicative work. By the end of the second semester the CI has worked with each student on at least five written and two oral reports. To help facilitate connections between the courses, the CI also keeps a log of individual difficulties and progress to help students identify their specific strengths and weaknesses in writing and speaking.

Although the CI is integral to our program, we realize that hiring a person without a chemical engineering background creates too sharp a distinction between the technical and communicative elements of written and oral work. In reality, a well-written report or speech must be both technically correct and well composed; the two aspects cannot be separated. To a large extent, the existing division is lessened by the interactions between the CI, the professor, and the TA. To achieve successful results, the communication work must be approached as an integral part of the course material. The professor must emphasize the importance of the writing and speaking assignments, not only when designing the course but also when addressing the students. Likewise, since the TAs grade the reports, they also must keep in close contact with the CI to help maintain consistency. When the communication component is given adequate value and acknowledgment, we have found that the artificial division between communicative and technical elements can actually help the students recognize that outstanding technical knowledge means little if they cannot effectively communicate their knowledge.

A second difficulty in hiring a non-technical instructor is that some understanding of the material is necessary for a complete reading. Fortunately, since basically the same material is covered each semester, the CI can become familiar with it over the course of several semesters.

One benefit of involving a non-technical instructor is the opportunity it provides for students to communicate with someone who does not share their

**TABLE 4**
**Checklist for Collaborators**

*Collaborative writing requires that you read and edit your peers' writing. Therefore, the following checklist is provided to help you identify areas which could be improved and revised in others' writing and in your own. Remember that revising takes time, and plan accordingly.*

**1. Check the overall organization of the draft.**

- ☐ Is the content presented in appropriate places? (*e.g.,* A discussion of results does not belong in the introduction.)
- ☐ Are the points sequenced logically?
- ☐ Is enough information included for complete comprehension? (Could the writer delete some information?)
- ☐ Does the report live up to its promises (from the abstract/introduction)?
- ☐ Does the writer avoid unnecessary repetitions?
- ☐ Are there logical transitions between the paragraphs/sections?
- ☐ Do the headings/subheadings help articulate the structure of the text? (Could the report use some subheadings?)

**2. Check the paragraphs.**

- ☐ Do the paragraphs keep to one central idea?
- ☐ Do the paragraphs reflect a continuity of logic?
- ☐ Does the writer avoid contradictions within a paragraph?
- ☐ Are the paragraphs an appropriate length?

**3. Check for style. Revise to make the language clear and direct.**

- ☐ Does the writer follow these principles for clear writing? (These are principles, not rules; apply them judiciously.)
  - Keep sentences short and to the point
  - Vary the sentence length
  - Use simple words
  - Avoid indirect expressions
  - Use familiar words • Avoid jargon • Define terms
  - Avoid unnecessary words
  - Write to *express*, not to impress
- ☐ Does the writer follow these guidelines for using vigorous verbs?
  - Use as many active verbs as possible
  - Avoid nominalized verbs, or verbs trapped inside a noun
  - Look for words ending in *-ion, -ment, -ing, -al* which could be made into an active verb
  - Try to change sentences which use wordy verb constructions, such as *there, this, it, these,* combined with forms of the verb "to be."
  - Ask if the verb should be past or present. Generally, describe work done in the past tense, and state principles and conclusions in the present tense.

**4. Check grammar, spelling, and punctuation.**

- ☐ Are the grammar, spelling, and punctuation correct to the best of your knowledge?

technical background. Although the oral and written reports are addressed to a technical audience, when working individually with the CI the students must express technical ideas to a non-technical audience. This actually helps to develop a better understanding of the material and is a challenging communicative exercise in itself.

Finally, we recognize that integrating communication training into existing courses does not allow for as much instruction as could be offered in a separate communication course. There is not enough time to require helpful reading materials on speaking and writing, or to evaluate and discuss published articles, or to offer workshops on writing and speaking. Many students would benefit from more intense instruction—particularly on technical writing. But, acknowledging that good communication skills are never "learned" once and for all, we feel that by providing some limited instruction and significant practice and evaluation, we are at least helping students to improve their skills. As one student remarked, his writing improved partly "because [he was] actually writing for a change." An integrative approach is certainly a step in the right direction. We also still encourage students to take communication courses outside the department and to use campus resources such as the "Writer's Workshop," a writing tutorial center sponsored by the Center for Writing Studies.

As we work to provide our students with better communication skills, we must remember that developing expertise in writing and speaking is a lifelong process. Integrating communication training into existing chemical engineering courses may not be extensive enough for some students, but it does provide a significant amount of practice in both speaking and writing, leaving students with some professional experience and, hopefully, with an awareness of the value of communication.

## ACKNOWLEDGMENT

The communication work reported in this article was developed by a number of individuals in addition to the authors: Dr. Charles A. Eckert, who initiated our emphasis on communication in collaboration with Marsha Bryant and Wayne Howell; Drs. Edward W. Funk, Thomas J. Hanratty, Douglas A. Lauffenburger, Richard I. Masel, Mark A. Stadtherr, K. Dane Wittrup, and Charles F. Zukoski, who all taught the courses; and Dr. Ruth Yontz, former Communication Instructor.

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# Process Control Lab Course

*Continued from page 187.*

The last experiment in the second phase is called "Hardware." In it, the students are required to study the features of Metrabyte cards such as DAS-8, DAC-02, DDA-06, PIO-12, and to hard-wire a data acquisition system for monitoring temperature in six polymer reactors with different initiators or different initiator concentrations. A multiplexer board (Metrabyte EXP-16) is used to connect the different thermocouples. The students thus learn about multiplexers, thermocouples (how the cold junction is set up on the EXP-16), A/D converters, D/A converters, electro-pneumatic transducers, and other important features in data acquisition and digital control. The reaction is then started, and the students monitor the temperature change in each reactor simultaneously. The students study the effect of changing sampling rate on data acquisition since six different temperatures are monitored simultaneously.

## CONCLUSIONS

These six laboratory experiments are an effective supplement to classroom lectures. Students gain hands-on experience in controller tuning, data acquisition, and control. Various process control concepts are emphasized, and the students develop a thorough understanding of the practical meaning of the concepts. The laboratory sessions cover almost all the topics discussed in class except certain advanced control strategies such as feedforward control or cascade control. Some of the available computer simulation packages are used to illustrate a few of these advanced control strategies. Interested readers may obtain complete information on the equipment or writeups of the experiment by contacting the author. ❐

# EXPERIENCE WITH A PROCESS SIMULATOR IN A SENIOR PROCESS CONTROL LABORATORY

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When we developed the senior process control laboratory at Lamar University, we acquired and installed a process simulator with full-fledged control and instrumentation. The process control laboratory has been a special-topic course in the undergraduate chemical engineering curriculum since the spring of 1992, and future plans call for a regular lab course to be taught along with it. A brief review of the development of the laboratory is the subject of this paper.

The process control laboratory was originally combined with the unit operations laboratory and included three analog units for level, flow, and temperature control in which the students were exposed to the tuning of 3-mode PID controllers by the Ziegler-Nichols method. These control units were designed and installed by Scallon Control, Inc., and the hardware was donated by Fisher Controls Company.

The need for developing computer-assisted labs became clear during the late 1980s.[1] As a first step, we developed a microcomputer-based pH control experiment in which the pH (process variable) of a given sample of water is controlled by adaptive control actions (variable gain). The process control laboratory currently also includes a PID tutorial program[2] and a video session for control valve selection and sizing.[3]

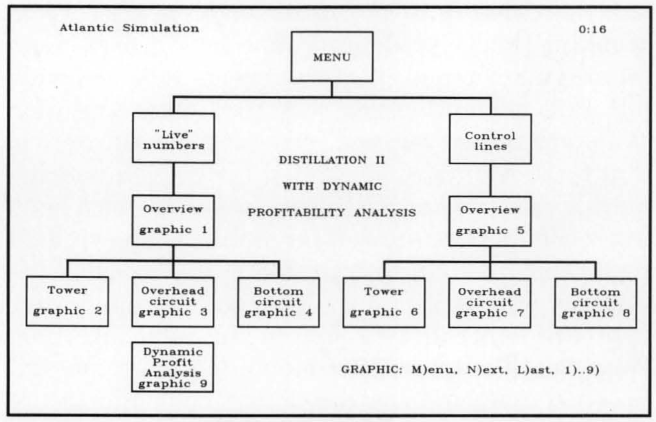


***Figure 1. Main Menu***

## PROCESS SIMULATOR

Industry needs engineering graduates who have a good understanding of plant practices in addition to their command of engineering fundamentals. Process simulators help students gain those insights by giving them hands-on experience with plant-wide process control. The Atlantic simulator was chosen primarily because it is PC based and we wanted to be able to use existing personal computers as

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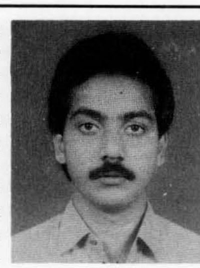

***Jack R. Hopper*** *is Professor and Chairman of the Chemical Engineering Department at Lamar University. He has had over thirty years of industrial and teaching experience, holds four US patents, and has over fifty publications in a variety of fields. Current areas of interest are waste management and minimization.*

*The process control laboratory has been a special-topic course in the undergraduate chemical engineering curriculum since the spring of 1992, and future plans call for a regular lab course to be taught along with it. A brief review of the development of the laboratory is the subject of this paper.*

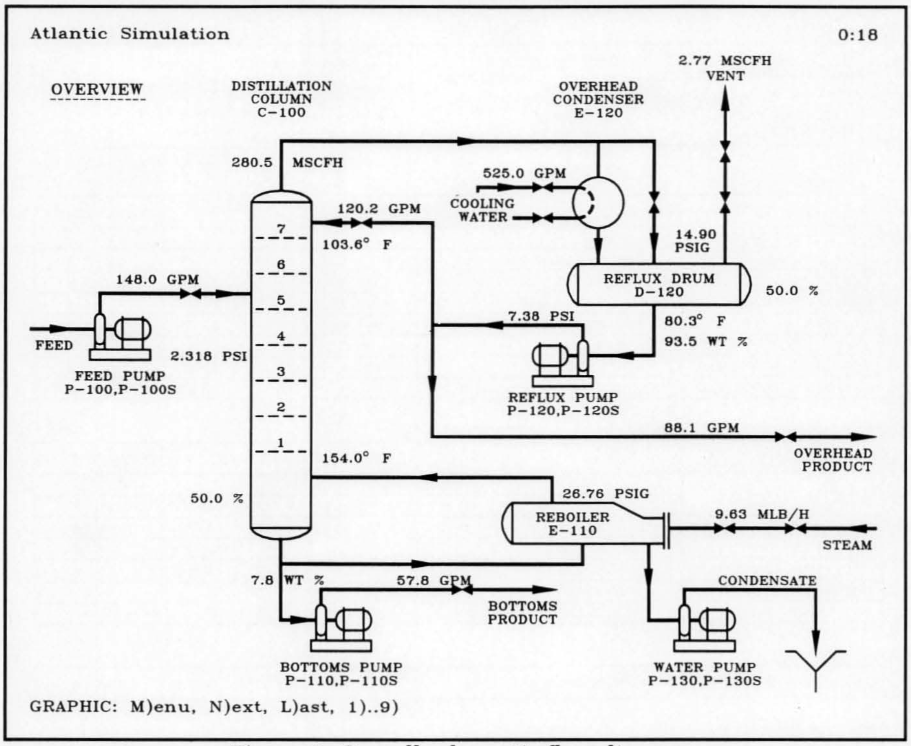


***Figure 2.*** *Overall schematic flow diagram*

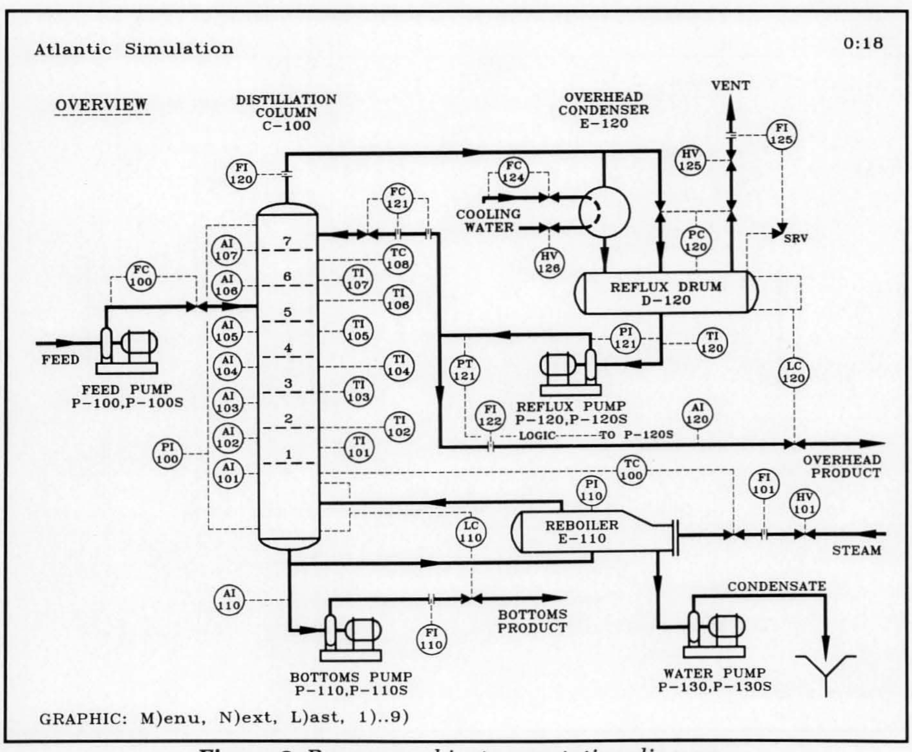


***Figure 3.*** *Process and instrumentation diagram*

workstations (for obvious economic reasons).

The newly acquired Atlantic process simulator simulates a typical distillation (depentanizer) process with the equipment and control structure similar to that in industrial plants. The column (seven trays) separates a binary liquid feed mixture containing 60% pentane and 40% hexane by fractional distillation. Figure 1 shows the main menu from which the desired graphic (schematic diagram) can be selected by entering the appropriate "graphic" number. The simulator graphics 1 through 4 are schematic flow diagrams, and 5 through 8 are process and instrumentation diagrams (see Figures 2 and 3). Simulator graphic 9 is the Dynamic Profitability Analysis (shown in Figure 4) which summarizes the cost aspects and keeps updating the profit/loss being made at that particular time. This helps the students gain insight into how process disturbances can affect plant profitability and highlights the necessity of bringing the process back to normal efficiency.

Figure 5 shows the instrument group screen. The set point of any instrument can be changed from this screen by selecting the required loop, and the control valve mode can be changed from automatic to manual in order to alter the manipulated variable. The trend of any instrument can be seen from the group trend screen—the simulator plots the trends of any four instruments at a time, taking either five samples per minute or one sample per minute on a time scale from -12 minutes to 0 minutes. The trends are plotted vertically instead of horizontally. Figure 6 shows the trend of the following instruments when the tower feed pump fails and actions are taken to rectify the disturbance:

1. FI-122 Top product flow indicator
2. FIC-100 Feed flow control valve
3. FI-110 Bottom product flow indicator
4. FI-101 Reboiler steam flow indicator

The simulator runs on two IBM 386 workstations. The hardware for each workstation consists of

- A fully configured IBM 386 with Microsoft DOS 3.2
- Floating point 80387 coprocessor
- 640K RAM
- One serial port
- One parallel printer port with cable
- Monochrome card and monitor with cable
- EGA card (256K RAM) and monitor with cable
- Hard disk
- Two floppy diskette drives
- One Epson dot matrix printer
- Operator TDC 3000 keyboard

The software consists of

- Control System Emulation software
- Instructor Station software
- Pecan Power System Operative Environment
- Process Model

## COST

The software, including the operator's keyboard with cable (per unit) costs approximately $25,000 (the listed price as of September 1991), but considerable discount can usually be obtained by educational institutions. The above cost also includes installing the software and training staff to operate the system. All other hardware listed above is extra.

## PROCESS MODEL

The Atlantic distillation model is based on first principles of physical phenomena (unsteady state heat and mass balance with thermodynamic properties). It is capable of providing proper dynamic response under normal operations, cold

Atlantic Simulation 0:23

D Y N A M I C  P R O F I T A B I L I T Y  A N A L Y S I S

| DEBITS | COST | USAGE | TOTAL USAGE | $ SPENT | TOTAL SPENT |
|---|---|---|---|---|---|
| COLUMN FEED | 1.000 $/GAL | 148.0 GPM | 3915 GAL | 8880 $/HR | 3912 $ |
| VENTED MATERIAL | 67.0 $MSCF | 2.77 MSCFH | 1.22 MSCF | 185 $/HR | 82 $ |
| REBOILER STEAM | 8.00 $/MLB | 9.63 MLB/H | 4.25 MLB | 77.1 $/HR | 34 $ |
| COOLING WATER | 0.050 $MGAL | 525.0 GPM | 13886 GAL | 1.575 $/HR | 0.694 $ |
| TIME | 75 $/MIN | 45 MIN | 26 MIN | 0 $/HR | 0 $ |
| OFF-SPEC BOTTOMS | 0.040 $/%DV | N/A | N/A | 0 $/HR | 0 $ |
| OFF-SPEC OVERHEAD | 0.030 $/%DV | N/A | N/A | 0 $/HR | 0 $ |

| CREDITS | PRICE | PRODUCTS | TOTAL PRODS | $ EARNED | TOTAL EARNED |
|---|---|---|---|---|---|
| BOTTOMS PRODUCT | 1.500 $/GAL | 57.8 GPM | 1528 GAL | 5200 $/HR | 2291 $ |
| OVERHEAD PRODUCT | 1.250 $/GAL | 88.1 GPM | 2331 GAL | 6611 $/HR | 2912 $ |
| OFF-SPEC BOTTOMS | 0.020 $/%DV | N/A | N/A | 3 $/HR | 1 $ |
| OFF-SPEC OVERHEAD | 0.035 $/%DV | N/A | N/A | 11 $/HR | 9 $ |
| BOT COMP (7.8 WT%) | N/A | 7.8 WT % | 7.8 WT % | N/A | N/A |
| TOP COMP (93.4 WT%) | N/A | 93.5 WT % | 93.5 WT % | N/A | N/A |
| TOTALS | N/A | N/A | N/A | 2680 $/HR | 1196 $ |

GRAPHIC: M)enu, N)ext, L)ast, 1)..9)

***Figure 4.*** *Dynamic profitability analysis*

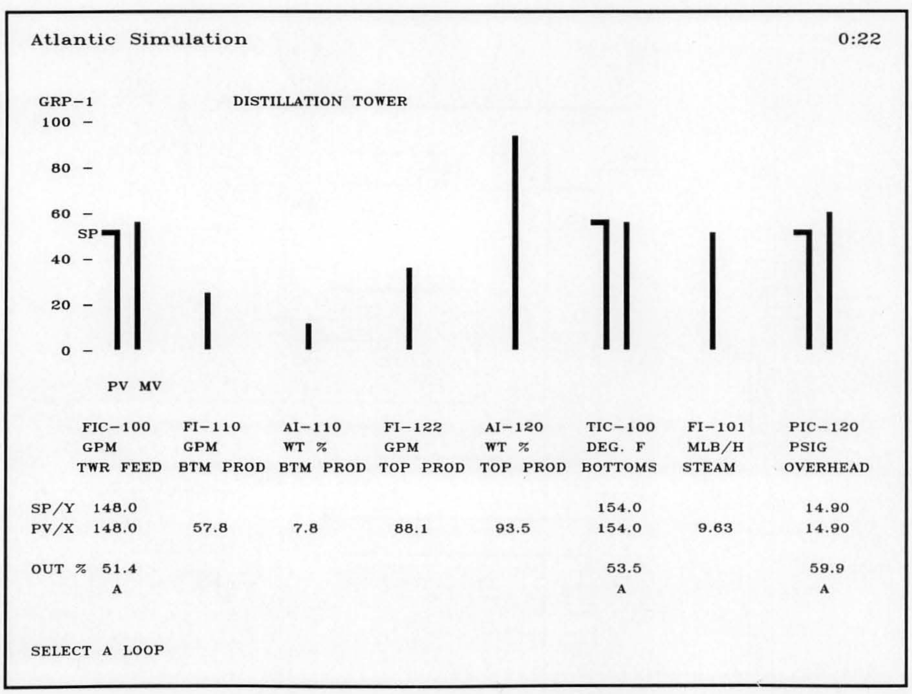


***Figure 5.*** *Instrumenrt group screen*

starts, emergency shutdown, normal shutdown, and plant upsets.

The distillation tower is modeled as approximately eight equilibrium stages. Each stage has few trays, and the vapor and liquid leaving each stage are considered in equilibrium. The dynamic component balance, heat balance, and total mass balance are maintained on each stage of the tower simulation. This assures heat and mass balance at all times in all modes of operation. Based on the tray data, vapor pressure curves are generated for all the components at various temperatures. The vapor pressures of components at startup conditions are also entered into the database along with vapor pressures obtained at design tray temperatures. The stage equilibrium calculations are performed using Raoult's law. The activity coefficient calculations are required if nonideality needs to be considered. The time constants for heat and mass balance equations are based on the mass hold up on the trays and heat capacities. The metal heat capacity can be included but is often ignored to speed up the simulation response time so that a startup can be exercised within a reasonable training session.

All the differential equations for the distillation simulation are solved using the Euler integration method. Because of the steepness of vapor pressures at various temperatures, Atlantic has developed a proprietary subroutine (tray) to solve all the stage differential equations simultaneously using numerical methods.

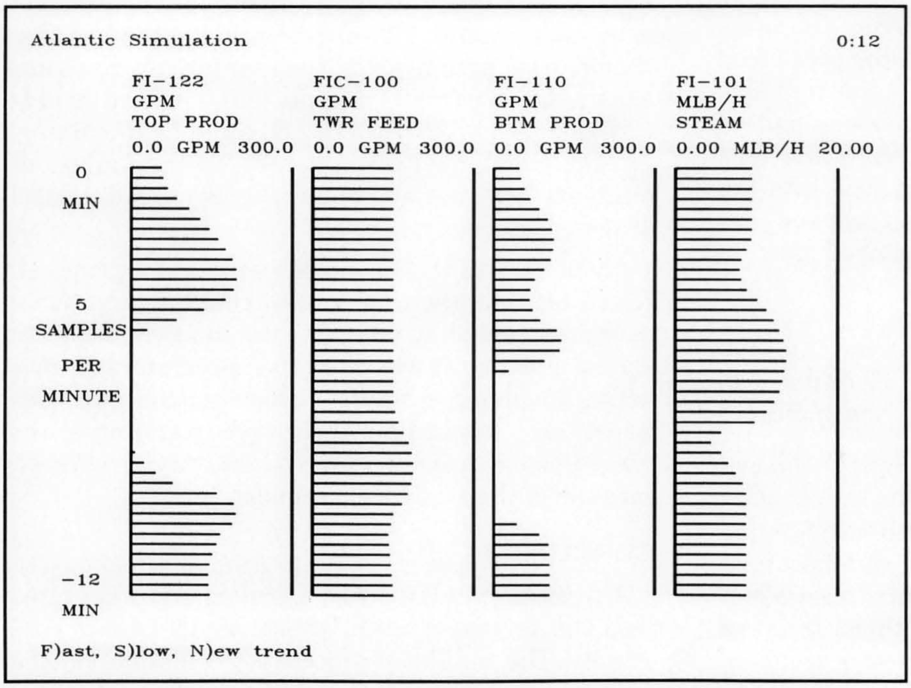


***Figure 6.*** *Instrument group trend (feed pump failure)*

## INSTALLATION

The company recommendation was that the computers be totally dedicated to the simulator, but since the simulator lab is offered only during the spring semester, we did not feel that exclusive dedication of two of our computers to the simulator would be desirable. In order to test the idea of a non-dedicated system, one computer was loaded with the simulator only and the other was loaded with the simulator and additional software. We then checked the performance of both simulators and found that both worked the same. Extra precautions should be taken, however, to ensure that students using other software check their disks for any viruses before inserting them into the computer.

## LABORATORY SCHEDULE AND EXERCISES

After allotting time for other experiments and assignments in the process control lab, we were left with only five weeks for the simulator training. With this limited amount of time we had to select a few "typical" exercises from the manual. After we had reviewed the manual, practiced, and trained ourselves, the following program outline was decided upon:

***Week 1*** Familiarization with the process, control philosophy, and keyboard operation

***Week 2*** Correction of known disturbances

***Week 3*** Identification and correction of unknown disturbances

***Week 4*** Cold start-up

***Week 5*** Buffer for any incomplete work and report submission

The process control lab was scheduled once a week. In order to accomodate fourteen students, we split them into six groups and each group was allotted 1 hour and 50 minutes per session.

In the exercise for correction of known disturbances, the students practiced the corrective actions to be taken when some particular disturbance occurs (*e.g.,* when the feed pump stops, the cooling water block valve closes, the reboiler tube fouls, pentane concentration in feed increases, the ambient temperature changes, etc.).

In the exercise for identification

and correction of unknown disturbances, a disburbance was introduced through the instructor's console and the students had to identify and correct the problem. The time taken by the students to identify the disturbance and to subsequently correct the process was observed.

After the students became familiar with the "normal" operations, they were asked to work on the cold start-up exercise, which gives a step-by-step procedure to start/commission the column. Finally, the students had to submit a report on the whole simulator program.

## STUDENT RESPONSE AND PERFORMANCE

Once the students became familiar with the simulator, they showed more interest in the system. In addition to the exercises assigned to them in the lab, some of the students worked on almost all of the equipment failure exercises given in the manual. On the whole, the students' performance in identifying and correcting equipment failures was more than satisfactory. Atlantic Simulation, Inc., recommends certain time limits for identifying and correcting equipment failures: 82% of the students could identify, and 100% of the students could correct, the equipment failures within the stipulated time. Most of the students also successfully completed the cold start-up of the plant to the normal operating conditions.

Most of the student's perception of the overall process was very good, and they learned a number of fundamental aspects of plant operation. For example, when a feed pump fails, after identifying the problem the student would normally start the spare feed pump without realizing that the flow control valve on the pump discharge was wide open as a result of no feed flow—immediately starting the spare feed pump could cause an excess flow of feed into the column, creating more problems. They learned that the flow control valve must be switched over to manual mode and closed to about 20% before starting the spare pump—the valve must be manually opened to obtain the required design flow and then switched back to the automatic mode. Knowing such operational aspects definitely helps young engineers do a better job.

## STUDENT FEEDBACK

Since this was the first time the Atlantic Simulator was included in the process control laboratory, we needed feedback from the students to assess how useful the simulator had been to them from an engineer's viewpoint. A questionnaire was prepared for this purpose. We felt the feedback would also be valuable to us in making further improvements in the training program.

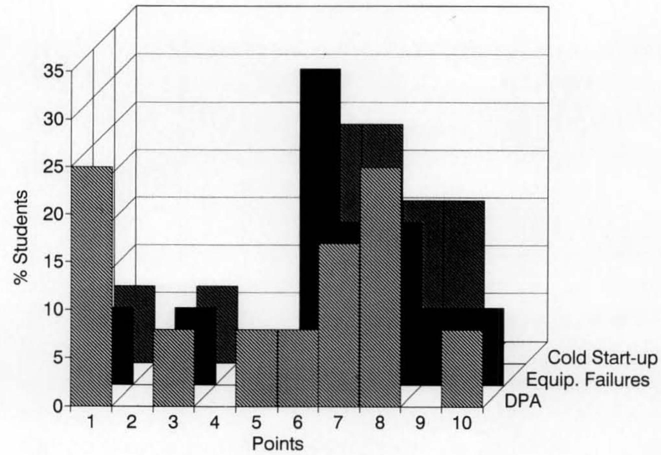


*Figure 7. Distribution of student evaluations of the simulator*

From an engineer's standpoint, 75% of the students felt that the simulator training was "useful," and 25% considered it "very useful." Figure 7 presents the students' point-evaluation of the equipment failure exercises, the cold start-up exercise, and the dynamic profitability analysis (DPA). It shows that about 67% of the students gave points ranging from 6 to 8 (out of a maximum of 10) for the cold start-up and equipment failure exercises. The students' opinion of the DPA, however, has not been as consistent as in the other two cases.

There is only one cascade control loop in the process, and all of the students said that the simulator did not help them to better understand the concept of cascade control. This could be due to the fact that the program assumes that the user already has some knowledge of control concepts and does not include an explanation. Another reason could be the timing, *i.e.,* the simulator lab was scheduled right after our students have gone through the advanced control scheme lectures.[4]

About 60% of the students wanted more time allotted for this program so they could do additional exercises, including emergency shutdown exercises. To the question of whether other simulators for processes involving reactors, absorption columns, furnaces, etc., would help their understanding of the operation of plants and process control concepts, almost all of the students responded "yes."

## CONCLUSION

A process simulator was installed and integrated into the process control laboratory at Lamar University. The simulated process is the distillation of a C5/C6 feed (depentanizer). Based on student performance and feedback, the simulator training is deemed to have been successful. In addition to learning certain fundamental aspects of plant operations and plant-wide process control, the simulator was also useful in emphasizing safety aspects such as emergency shutdown procedures. For new engineers, knowledge of operational and safety aspects could be a real asset when they begin work.

To summarize, the simulator was well received by the students and was regarded by the instructors as an effective teaching tool.

## ACKNOWLEDGMENT

Financial support from the Amoco Foundation for the development of the process control laboratory is gratefully acknowledged. We also acknowledge Chetan R. Amin, Mike Kroll, and Joe Siebem for providing us with the details of the process model.

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## REVIEW: *Chemical Engineering, Vol. 2*

*Continued from page 183.*

Experience and judgment are evident in the explanations and discussions of the basic science and industrial usage. A level of comparative knowledge is offered that is often omitted from other texts in favor of physics and mathematics. The reasons why one process is chosen over another in industrial applications are explained. In a section on membrane separations of biological materials, a philosophy is suggested for selecting a process: follow the way in which nature has solved the problem. For example, even though dialysis is a slow process unsuited for large-scale industrial separations, its gentle treatment of blood is appropriate for hemodialysis. The discussion of ion exchange delves into the polymer chemistry of the cationic and anionic resins that facilitate the range of applications of this important unit operation. Motivation is provided for the understanding of drying as a process following evaporation, filtration, or crystallization, to improve handling and reduce transportation costs. A brief description of fluidized-bed catalytic cracking explains the essential features of this outstanding achievement of chemical engineering. Insightful explanations such as these are one reason why this reviewer will open this book before some other engineering handbook when seeking background information on a separation technique.

The topics covered include chapters on: Particulate Solids; Size Reduction of Solids; Motion of Particles in a Fluid; Flow of Fluids through Granular Beds and Packed Columns; Sedimentation; Fluidization; Filtration; Gas Cleaning; Centrifugal Separations; Leaching; Distillation; Absorption of Gases; Liquid-Liquid Extraction; Evaporation; Crystallization; Drying; Adsorption; Ion Exchange; Chromatographic Separations; Membrane Separation Processes.

To illustrate the depth of treatment, consider the chapter on sedimentation. Sections fully describe topics on terminal velocity, height of suspension, shape and diameter of vessel, effects of suspension concentration, Kynch theory, flocculation, settling of coarse particles, and analysis of a continuous thickener. A separate chapter deals with centrifugal separations, including centrifugal pressure and shape of the liquid surface, separation of immiscible liquids, sedimentation, filtration, mechanical design, and equipment descriptions. The chapter on adsorption treats the nature and structure of adsorbents, adsorption equilibria (including mathematics of Langmuir, BET, Gibbs isotherms, and Polanyi potential theory), kinetics, equipment, and regeneration (including thermal and pressure swing, parametric pumping, and cycling-zone adsorption). The exposition of these topics is clear and balanced.

To summarize: this book is a useful and usable contribution to the chemical engineering literature, welcome as an introductory text or as a general reference on separation and particle processes. ❐

**ChE book review**

## *PLASTICS RECYCLING: PRODUCTS AND PROCESSES*

Edited by R.J. Ehrig
Oxford University Press, 200 Madison Ave., New York, NY 10016; $64 (cloth), (1992)

***Reviewed by***
**Charles Beatty**
**University of Florida**

This is an excellent primer on the products and processes used in the early phase of plastics recycling. It covers the commodity plastics that are available for recycling in reasonable volumes. For this

*Continued on page 219.*

# GRAND WORDS, BUT SO HARD TO READ!

## *Diction and Structure in Student Writing*

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*University of Waterloo*
*Waterloo, Ontario, Canada N2L 3G1*

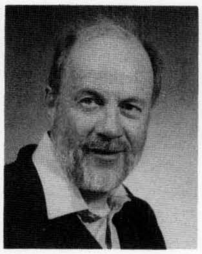
What makes student reports so hard to read? After all, students are a pretty competent lot, are they not? Can't we assume, therefore, that they write well too—that technical competence and writing ability go hand-in-hand?

Not at all.

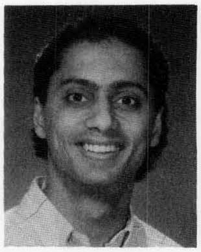
The skill with which most students manipulate differential equations or design PID controllers is rarely reflected in the way they *write* about these things. Although few of them commit the worst faults (ungrammatical sentences, dangling modifiers, and heavy reliance on the passive voice), even the best students often produce muddled prose. Why?

The answer, we think, lies in two chief faults of student writing: sloppy, imprecise use of words and phrases and a disregard for the natural sequence of ideas that the reader expects. In this paper we will show, using examples of student writing, how even the most straightforward technical material can become confused, obscure prose when not enough attention is paid to choosing just the right word and to arranging ideas in a coherent manner.

How can we improve our students' technical writing? Merely pleading with them to choose and arrange their words carefully is not enough. We must first convince them that learning to write well is not only essential in communicating their ideas to others, but that it is also fundamental to the act of *learning* itself. Morton Denn, former editor of the *AIChE Journal,* said,[1] "Skill in communication is closely tied to the way in which an individual formulates and approaches problems, *and the failure of schools to emphasize writing has had a major impact on technical education and professional practice"* (our italics). His observation, though a little disheartening, suggests a tantalizing question that is certainly worth mulling over—by making our students better writers, can we also make them better engineers?



**Bob Hudgins** *holds degrees in chemical engineering from the University of Toronto and Princeton University. He teaches about stoichiometry, unit operations and reaction engineering, and studies the periodic operation of catalytic reactors.*



**Aloke Phatak** *obtained his BASc and MASc in chemical engineering from the University of Waterloo and is presently working on his ChE doctorate. His thesis topic is applications of multivariate statistics in chemical engineering, and he also has a strong interest in technical writing.*

## THE PURPOSE OF TECHNICAL WRITING

### *How do Diction and Structure Fit In?*

*Now, what I want, is Facts . . . . Facts alone are what are wanted in life . . . . Stick to the Facts, sir!"*

Thomas Gradgrind
in Charles Dickens' *Hard Times*

Students often forget that the purpose of technical writing is not merely to present facts and information, but also to *communicate* them. In other words, as Gopen and Swan put it,[2] "[it] does not matter how pleased an author might be to have converted all the . . . data into sentences and paragraphs; it matters only whether a large majority of the reading audience accurately perceives *what the author had in mind"* (our italics). To communicate clearly, effectively, and persuasively without misleading the reader, therefore, the writer must choose words carefully and structure ideas logically so that the reader knows precisely what is meant.

> ***The skill with which most students manipulate differential equations or design PID controllers is rarely reflected in the way they write about these things . . . even the best students often produce muddled prose.***

Our choice of words and phrases, or *diction* in the language of grammarians, determines the accuracy and clarity of our writing. Proper diction might not seem, at first sight, to present much of a problem in scientific writing. After all, engineers and scientists write about concrete things—models, simulations, controllers, packed-columns, reactors— and how they work. Finding the right word or term should be easy, especially in the straightforward writing we demand of our students. But in technical writing we also describe, analyze, recommend, argue, and discriminate. To do these thing well and without ambiguity, we must be mindful of selecting exactly the right words. Yet, either consciously, to hide their ignorance, or unconsciously from sheer sloppiness, students often choose their words poorly, with the result that sometimes we don't know what they are trying to say, or indeed, whether *they* really understand what they are trying to write about!

Good diction, however, is only one ingredient of clear prose. We must also strive for coherence when presenting information or arguing a point. In student writing, ideas within a paragraph are often presented in a haphazard fashion, with no thread to bind them together. The result, as with poor diction, is confusion and frustration in the mind of the reader. No matter how carefully the sentences in a paragraph are crafted, the ensemble will mean little if there is no logical connection among its constituent units. To avoid confusion and to present ideas as smoothly as possible, the writer must be careful about *where* he places information within a single sentence and within groups of sentences. The arrangement of this material is what is meant by the *structure* of prose. In a well-structured paragraph, the beginning of a sentence looks back to what was just said, while the information at the end of the sentence represents new material that the author wants to introduce. In this way the reader always knows where he is in the exposition or discussion. Like Theseus, he always has his hand on the thread (here, the thread of the argument) and will have little trouble finding his way about even the most labyrinthine discourse.

In the following two sections we will look at some examples of student writing that illustrate what happens when words are poorly chosen and when the expectations of the reader about where information should appear are not fulfilled. The result is that even simple, straightforward technical material becomes very difficult to follow.

### DICTION

*Alice had no idea what Latitude was, or Longitude either, but thought they were nice grand words to say.*[3]

Lewis Carroll
*Alice's Adventures in Wonderland*

Student reports are often full of big, "scientific-sounding" words, some of which are chosen solely to impress the reader. Here is just one example:

> *Step tests were run to determine the boundaries of the problem statement (i.e., the valve positions at 75°C and 85°C).*

Grand words indeed, but what does "boundaries of the problem statement" really mean? Were the students really interested in characterizing the "problem statement" itself? Or, if we carry their words to the extreme, can valve positions have boundaries? Using pompous expressions or words can lead to absurd statements like the one above and can confuse the reader. After reading the sentence a couple of times, we still do not know why the students carried out step tests. Unfortunately, such inflated, imprecise prose is common in student writing. Consider the following:

> *Due to the stochastic nature of the conclusions of this study, no real difference between the two statistical methods could be ascertained.*

It is clear that the author found no difference (the word "real" is superfluous here) between the two methods, but *how* and *why* he came to such a conclusion remain a mystery. Indeed, if we are to take the author literally, rational enquiry is of little use to either him or to us—our conclusions themselves are subject to the laws of probability!

In the two examples just presented, the students used pretentious expressions such as "boundaries of the problem statement," "stochastic nature of the conclusions," and "ascertained" to project an air of unassailable authority. In the second example, however, there is another objective: to hide what the author thinks is a result for which he will be penalized. Instead of saying the obvious (something like "the two methods yield the same result"), he feels compelled to embellish such a simple, straightforward statement; in the end the effect is more comic than convincing.

Yet another group of students writes:

*The same tuning constants [that we used in the simulation] were used with PID control on the actual process. The response was found to be less than excellent. . . . This indicates that the simulation is lacking in the heat rejection department.*

The faults in this example are too numerous to list. We note, however, that here the students have managed to combine obfuscation with pomposity by using terms such as "less than excellent" and "heat rejection department." In addition, the second sentence is particularly confusing. Was the *response* of the process (to a step input, set-point change, etc.) poor, or was the *agreement* with the simulation poor?

As we stated earlier, poor diction confuses the reader and leaves him doubting the writer's grasp of the subject. For example, here is how some students described a computer simulation of a stirred-tank heater:

*The system was modeled using two different simulations. One simulation was based on the Euler equation, while the second simulation was based on the Runge-Kutta #4 equation.*

Nonsense. First, there may have been two simulations, but there was only one *model*, one set of differential equations. Second, numerical methods of integration do not form the basis of any simulation. Third, Euler, Runge, and Kutta wrote many equations; which ones do the authors mean? Here, the students are unsure of the meaning of the words *model* and *simulation;* hence, they "model" a system using a "simulation," and they base their simulations on numerical methods of integration!

In our last example we find the following:

*The model is only as good as the system parameters as identified by the experimental tests. It is assumed that the process parameters found in the experimental tests are an accurate representation of the process.*

Confusing? What if we replace the word *model* in the first sentence with *simulation?* Although the sentence is still faulty, we can now begin to understand its general meaning—something like "If the parameter *estimates* are unreliable, the simulation will be too!" In the second sentence, excess verbiage ("an accurate representation of the process") camouflages what we think is the authors' real intent: to say that the parameter estimates they obtained were indeed reliable. Here, as in the previous example, poorly chosen words and phrases leave us wondering how well the students have grasped certain fundamental notions such as the distinction between a model and a simulation, what parameters and parameter estimates are, and how engineers "represent" processes.

In most technical writing we would like to choose the right word to be as precise as possible, not to satisfy requirements of nuance, balance, rhythm, and subtlety. Technical terms usually have a single, precise meaning and cannot always be interchanged—if we mean "parameters" we should not say "parameter estimates," and if we are describing a "model" we should not use the word "simulation" in its place. At the same time, however, scientific prose is more than a mere list of technical words—it also requires verbs, adjectives, and adverbs. It is here that students are tempted to use vague, imprecise phrases, either out of a desire to obscure the real meaning or simply out of sloppiness. If students find that two different methods give the same results, they are not likely to choose the simplest words to say so but will write instead that "the two methods could not be differentiated" or "the two methods yield approximately the same conclusions." Choosing just the right word is hard work, but it is essential to do so to say exactly what is meant. Good diction enforces clarity, accuracy, and honesty in writing—essential components too of scientific investigation.

### STRUCTURE

*[Writers] should, whenever possible, prepare their readers for new information by beginning their sentences with a "topic," ideas that are familiar to the audience or that have already been referred to, and then moving to . . . newer, less predictable, less familiar information*

*By consistently choosing to arrange information in this way, writers . . . enhance the coherence of their documents . . . .*

J. M. Williams[4]

Most technical reports are divided into logical units called sections. For example, a typical document might be structured in the following manner: Introduction, Experimental Method, Results and Discussion, and finally, Conclusions and Recommendations. Not only do most readers expect this structure, but it also provides a framework in which the writer can logically present an analysis or argument. Imagine, for example, trying to read a discussion of results before any results have been shown!

Just as a report is arranged into logical units, so too can a sentence be divided, although its functional divisions are not explicitly labeled.[2] This way of looking at the structure of prose has been formalized in a linguistic principle known as *functional sentence perspective.* In brief, it states that a sentence should begin with a "topic" idea, information that is familiar to the reader, and then move on to the "stress position," an idea or information that is less familiar, more complex, and more important[4, p. 93]. Organizing a sentence in this way not only makes the flow of ideas more coherent and less choppy, but it also ensures that the reader understands exactly what the writer is trying to emphasize.

The expected structure of a sentence can be portrayed very simply as

| Expected Sentence Structure | | |
|---|---|---|
| Topic position → | verb → | stress position |
| (refers to old information) | | (new information) |

The first part of the sentence (the topic) refers to a particular subject and looks backward to ideas that have already been presented, usually in the preceding sentence. New information is then located toward the end of the sentence (the stress position). This repeated overlapping of the new information in one sentence by the topic of the next s uggests, we think, a particularly apt metaphor—the laying of shingles. By "shingling" his sentences in this way the writer can lead the reader from start to finish, from premise to conclusion, in a methodical manner.

What happens when we violate this principle? Take a look at the following example of student writing in which the authors paid little attention to the smooth flow of ideas.

*The chemical engineer is often faced with the problem of analyzing the relationship between two large sets of process data. In the past, multivariate statistical methods have primarily been applied in the social sciences. Due to the large amount of data generated by industrial processes, chemical engineers need these types of statistical tools. The purpose of this report is to investigate two different methods . . .*

Each sentence above makes sense when read by itself. Strung together in the way they are, however, means that we have to read the passage several times before we can understand what the authors are trying to say: that for certain types of statistical analyses, chemical engineers need tools that, until now, have been used mainly in the social sciences.

Why is the passage difficult to follow and to understand? The first sentence sets up certain expectations in the reader's mind about what is being discussed—the analysis of large sets of process data. In the second sentence, however, we are confronted with new information ("multivariate methods in the social sciences") that has no connection to what we have just read. At the end of the second sentence we move on to the third with the term "social sciences" fresh in our minds—but again, we encounter a topic ("data generated by industrial processes") that has nothing to do with what we have just read. By violating the reader's expectations of what he *expects* to read at each step and by beginning each sentence with a topic that does not refer to old information, the authors have written a passage that has no focus.

In the second example, another group of students writes:

*Over a period of time, weak acids, sodium mercaptides and sodium sulphides accumulate in the prewash caustic, requiring the spent caustic to be replaced periodically. A strong odour in the spent prewash caustic indicates that the process is running inefficiently. In the #1 plant, when the caustic needs to be changed, the column is completely drained of spent caustic and replaced with fresh caustic. When the caustic is dumped it is sent to a spent caustic storage tank.*

Here, as in the first example, we can understand the individual sentences, but we have no sense that anything ties them together. The reader is confronted in the topic position of each sentence with completely new information. Thus, going from start to finish occurs in a series of jerky movements, and we are not sure just what the writers are trying to emphasize.

The above discussion of expected sentence structure presents a much simplified picture. For example, the topic may refer to an idea farther back than the preceding sentence. Furthermore, the size of the stress position can vary quite a bit. In some sentences it may be as short as a single word, while in others it may extend over several lines.[2] Nevertheless, if the writer follows the simple paradigm pictured above within single sentences and within groups of sentences, the reader will be able to follow, with little effort, the flow of the argument. The following example illustrates this point:

*In suspension polymerization the conversion of monomer to polymer takes place in the aqueous phase. At the end of the reaction, the slurry contains not only polymer and monomer but also emulsifier and other water-soluble impurities. Because these impurities affect the quality of the final product, they must be removed from the polymer. Thus, the method of drying the polymer is of prime importance.*

The first sentence introduces the general subject (suspension polymerization) which, as the author informs us, takes place in the aqueous phase. The emphasis on water is followed by putting the word "slurry" in the topic position of the second sentence. The focus then shifts, in the stress position, to water-soluble impurities, and these reappear in the topic position of the third sentence. As the third sentence unfolds with a dependent clause ("Because these impurities . . ."), we begin to sense that something important is coming up, and by structuring the sentence in this manner the author makes it clear to the reader that it is important to remove

*Continued on page 209.*

# SAFETY AND WRITING
## *Do They Mix?*

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The chemical engineering profession has long voiced a concern that engineers often graduate with inadequate training in chemical safety and with less-than-desirable writing skills. Some educators have reacted strongly to these concerns and, in response, have developed entire courses on chemical safety[1] and technical communications.[2] Pitt[3] has argued the futility of teaching laboratory safety and suggested the "benefit of 'safety awareness' teaching must be to increase people's motivation." Educational research has found writing "a unique mode of learning—not merely valuable, not merely special, but unique . . . higher cognitive functions, such as analysis and synthesis, seem to develop most fully only with the support of verbal language—particularly it seems, of written language."[4] If we can, therefore, uniquely blend safety and writing into our curriculum, we create a possible mechanism to motivate our students' safety awareness.

This paper highlights how I have blended safety and writing into my laboratory instruction to improve both safety awareness and written communication. This experience should offer creative ways for other engineering educators to effectively and efficiently integrate safety and written communication into their own curriculum.

### MOTIVATION

We offer a two-course unit operations laboratory sequence which our majors take in their sixth and seventh semesters. The laboratory projects in one course (one credit hour) emphasize momentum and heat transfer principles, while the second course (two credit hours) emphasizes mass transfer operations. Using lectures and laboratory demonstrations sprinkled throughout these two courses, we introduce the students to the elements of statistical analysis of data, experimental design, and model build-

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ing. With these tools, they can then undertake "an appropriate laboratory experience" that satisfies the Accreditation Board for Engineering and Technology (ABET) curricular content criteria.[5]

With regard to safety and written communication, ABET's criteria clearly state that the engineering professional must have (the bold-face emphasis is mine)

- *. . .an understanding of the engineer's responsibility to protect both occupational and public health and **safety . . .***
- *The engineering design component must . . . include a variety of realistic constraints such as . . . **safety** . . .*
- *Instruction in **safety procedures** must be an integral component of the students' laboratory experience.*
- *Competence in **written communication** in the English language is essential . . . the development and enhancement of **writing skills** must be demonstrated through student work in engineering courses.*

The unit operations laboratory serves as a natural environment to meet those criteria. If we add to the laboratory other ABET criteria, such as design content, open-ended problems, and oral communication, we either dilute the "hands-on" experience of our three-credit hour laboratory sequence or transform it into a course deserving of six or more credit hours.

With the Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) starting to demand that university laboratories comply with federal regulations regarding chemical storage, waste disposal, and chemical hygiene, the task of meeting all the ABET, EPA, and

OSHA requirements becomes nearly intractable. Fortunately, our department offers a three-week, one-semester-hour course on chemical laboratory safety that all students enrolled in Freshman Chemistry must successfully complete by passing a written examination. This *passive* method of safety instruction, however, does not insure compliance with the federally imposed regulations. Therefore, we sought to devise a laboratory environment which *actively* promotes safety as well as meeting the ABET, EPA, and OSHA requirements.

## APPROACH

The problem of cramming more material into a limited curriculum needed addressing. My solution was to merge two seemingly unrelated topics—safety and technical writing. I patterned this integration of safety and written communication after a similar structure at Dupont's Seaford Nylon Plant, where I had previously worked. At Seaford, the safety program actively involved everyone from the technical superintendent right down to the clerk typists. Stressing personal responsibility for a safe workplace seemed to instill a strong sense of safety awareness in the participants. Since safety audits served as a good means to actively involve the people at Dupont, I decided such an activity could work equally well with my unit operations laboratory students.

All successful businesses require frequent and concise communication between their operating units. The company memorandum is the principal mode of written communication because it promotes a rapid exchange of clearly and concisely written information. Similarly, I adopted the memo as the principal way for our students to communicate within the laboratory. It allows me to quickly cut to the essence of the students' work without spending hours reading comprehensive reports. Others have used memos and other short written communication techniques for similar reasons.[2,6-8]

## COURSE SETTING

Our blending of safety and technical writing occurs in the mass transfer operations course, which meets weekly for a one-hour common lecture and a five-hour laboratory session for the individual sections. Before the first laboratory session, I randomly assign the students to groups and projects. An individual student group has responsibility for only one project during the entire semester, and the group periodically issues written and oral reports to summarize its progress. To expose our students to the other laboratory projects, the groups having primary responsibility for each project plan short experiments for the other groups to perform during scheduled visitations to their projects. Such a laboratory structure openly promotes active communication between groups.

## LECTURE AND LABORATORY ACTIVITIES

In this section I outline the specific activities I have successfully used to teach safety with written communication in our undergraduate laboratories.

### *Safety Audit Team Reports*

During the second laboratory session I form two-person safety-audit teams, issue a semester schedule for the teams, briefly discuss what safety items the teams should look for, and send the first team off to inspect the laboratory (see Table 1). Some of the items to look for include properly operating safety shower and fume hood, clear access to exits, properly labeled chemical containers, frayed electrical cords, and water spills. They are also asked to correct any unsafe situation and report their findings in a memo.

The team must complete their inspection before the other laboratory groups can begin working, a

**TABLE 1**
**Safety Audit Team Checklist**

*Student-designed document used as a checklist for the safety audit teams. The results of the audit are then summarized in a memo and filed in a "red notebook." The procedure insures compliance with EPA and OSHA regulations.*

Safety Audit Team Check List
Unit Operations Lab

Room 110

| OK | Unsafe | Item | Item Description |
|---|---|---|---|
| | | 1 | Safety shower operates properly |
| | | 2 | Safety shower is easily accessible |
| | | 3 | Fire alarms and extinguisher are accessible |
| | | 4 | Chemical containers properly labeled |
| | | 5 | Walkways are free of clutter |
| | | 6 | Floors are clear of water puddles |
| | | 7 | Lab is neat and in good working order |

Comments:

Date: ________ Auditors: ____________________

process that takes about fifteen minutes. The very first audit uncovered a particularly dangerous situation—a safety shower that only a person over six feet tall could reach!

The students file these safety audit reports in a "red notebook" which I periodically review but do not grade. Should any safety item require immediate attention that the team cannot handle, they are instructed to personally contact the proper university personnel and to document the conversation in the audit report by also issuing a memo to the person they contacted.

After the first round of audits, I noticed that one student had composed a series of audit checklists for the five laboratory areas the teams had to check. Since these checklists greatly improved the team's efficiency, they were used in all subsequent audits. (Table 1 gives the checklist for one of the areas.)

This activity offers an excellent way to practice writing, to comply with EPA and OSHA regulations, and to encourage student ownership in creating a safe workplace.

### *Equipment Safety Analysis*

After some brief introductory comments about the semester project, I discuss the laboratory section that concerns performing an equipment safety analysis. Bethea's *NIOSH Instruction Module Units V and IX*[9] serve as a guideline for the discussion. In their analysis, I ask the groups to include a sketch of the floor plan of the laboratory area in which they work, to list chemicals used and the proper disposal of waste chemicals, to review MSDS's for toxicity, flammability and incompatibility, and to identify all electrical, mechanical, and tripping hazards. Each group then summarizes their analysis in a memo. In the following laboratory period, the graduate teaching assistant and I orally review this ungraded memo with the groups.

### *Writing Workshops*

During the common lecture period I run a series of workshops on technical writing in weeks two through four.

**Agents of Wordiness Handout** • The material I present on technical writing draws heavily from a short course I took in 1981 when I worked for Dupont, called the "Burger Course in Effective Writing."[10] Burger identified thirty-nine agents that contribute to wordiness, with the rankings indicating how frequently the agents occur (see Table 2). I distribute a handout that defines and gives examples of these agents, which I briefly review in the first lecture.

To warm students up to Burger's method, I start with a discussion of the number-one agent, "verb mutilation" and ask them to find the key verb thought in the first sentence in Table 3. This sentence mutilates the verb thought "to recommend" by turning it into a noun. The second sentence

**TABLE 2**
**Burger's Agents of Wordiness**

The following list Burger's compilation of agents that contribute to wordiness. Our discussion is limited to the first 29 agents since they occur more frequently than the last ten. We also suggest ways to eliminate them from the students' written communications.

| | |
|---|---|
| ***Overpoweringly Important*** | 21. Modifier mutilation |
| 1. Verb mutilation | 22. Pointless attribution |
| 2. Saying what goes without saying | 23. Repetition plus |
| 3. Disregard of common elements | |
| 4. Overuse of the passive | ***Important*** |
| 5. The zero word | 24. The Misattached modifier |
| | 25. The bangbang paraphrase |
| ***Very Important*** | 26. The name substitute |
| 6. Prepositionitis | 27. Noun mutilation |
| 7. The irrelevance | 28. The wrong "each"-type word |
| 8. The wrong point of view | 29. Failure to use prepositions |
| 9. Failure to use second-time words | |
| 10. The trivium | ***Unimportant*** |
| 11. Fractional anticipation | 30. Failure to use indirect objects |
| 12. Zigzagging | 31. "If" first |
| 13. The pointless modifying clause | 32. Name first |
| 14. The pointless third-level modifier | 33. Preposition first |
| 15. The impersonal introduction | 34. "The" first |
| 16. The wrong number | 35. Failure to use summary words |
| 17. The unnecessarily difficult verb | 36. The long-winded affirmative |
| 18. The club-member phrase | 37. Failure to use the possessive |
| 19. Pointless repetition | 38. Overuse of the possessive |
| 20. The long-winded negative | 39. Failure to use the passive |

**TABLE 3**
**Examples of Verb Mutilation and Other Agents of Wordiness Used in Writing Workshop**

*The boldface-type words designate the problem areas in the sentence. Eliminating these agents leads to a clear and concise sentence about half as long as the original.*

1. My **recommendation** for the new system is that we replace the fouled heat exchanger tubes.
   *Agents of Wordiness: Verb mutilation*
2. The **replacement** of the fouled heat exchanger tube **is recommended.**
   *Agents of Wordiness: Verb mutilation; Overuse of the passive*
3. **It is recommended that we replace . . .**
   *Agents of Wordiness: Impersonal Introduction; Pointless third-level modifier*
4. I **would recommend** we replace . . .
   *Agents of Wordiness: Unnecessarily difficult verb (conditional)*
5. I recommend we replace . . .

## TABLE 4
**Original Safety Rules Handout**

SAFETY

Safety is of the ultimate importance. The key to safety is your awareness of potentially dangerous situations. In this lab dangers include hazardous and flammable chemicals, moving equipment, and high-pressure steam.

SAFETY REGULATIONS

1. Goggles will be worn when corrosive chemicals are mixed from bulk, or dangerous chemical reactions are in progress.
2. Safety glasses are to be worn around moving machinery.
3. Loose ties, shirt cuffs, trouser cuffs, or other floppy cloth pieces are prohibited around moving machinery parts. Leather shoes and socks, or approved equal, are required at all times.
4. Cylinders of gas under pressure should be treated with respect. A dangerous situation is created if the valve portion is cracked from the cylinder. Gas cylinders should be locked to a solid structure when in use and when in storage. They should be locked to a cart when in transit. When not in use, safety valve-cap should be kept on the cylinder.
5. There will be no horseplay in the laboratory. The possibility of accident and serious injury is ever present.
6. Each member of the lab is responsible for knowing the location of 1) all fire extinguishers, 2) all safety showers, 3) all exits, and 4) all first aid supplies.
7. No cola bottles, food of any sort, paper cups, paper towels, or scratch paper is to be brought into or consumed within the laboratory.
8. There will be no smoking within the laboratory.
9. All containers of liquid must contain a label with the following information: name of material contained, strength or purity if known, date placed in container, name of person doing the placing. Any container not labeled is to be emptied, washed and returned to the storeroom.
10. Keep your work area neater than you found it.

## TABLE 5
**Safety Rules Rewritten to Reduce Wordiness**

SAFETY

Safety is everyone's concern. Awareness of potential dangers is the key to safety. Laboratory dangers include hazardous chemicals, rotating equipment, and high-pressure gases.

SAFETY PRACTICES

1. Goggles and protective footwear must be worn in the laboratory.
2. Loose clothing or jewelry are prohibited near rotating equipment.
3. Pressurized gas cylinders must be: securely anchored when in use, securely anchored and capped when stored, and strapped to a cylinder cart and capped when moved.
4. Horseplay is prohibited in the laboratory.
5. Everyone must know the location of all fire extinguishers, safety showers, exits, and first aid supplies.
6. Smoking, food and drink are prohibited in the laboratory.
7. All liquid containers must be labeled with the following information: contents, concentration, date, and experimenter.
8. Keep your work area clean.
9. Properly dispose of all chemical waste.

seems to improve the situation but it actually results in another mutilated verb as well as use of the passive voice. I offer the third sentence, but this choice results in "the impersonal introduction" (Burger's #15) and "the pointless third-level modifier" (Burger's #14), while the fourth sentence suffers from an "unnecessarily difficult verb" (Burger's #17). We finally settle on the fifth sentence as an acceptable choice.

**Safety Rules Review •** When I first came to the University of Missouri-Rolla, I inherited the set of Safety Rules for the unit operations laboratory (see Table 4). As I examined the document, I found it lush with Burger's Agents of Wordiness and decided it would provide an excellent platform from which to discuss safety and technical writing.

Table 5 represents a major revision of the Safety Rules which resulted in more than a sixty percent reduction in the number of words. The review process uncovered many less frequently occurring agents, such as "the name substitute" and "noun mutilation." It also revealed the need to add a rule about waste disposal. Inspecting these "rules" in more depth, we find they actually represent safe "practices" rather than rules. This switch builds a more proactive attitude about safety.

**E-Prime •** Bourland[11] introduced a writing system called E-Prime, a name he derived from the following equation:

$$E' = E - e$$

In this equation, E represents standard English and e represents all forms of the verb "to be." Therefore, E-Prime English eliminates the verb "to be" from use. This practice eliminates most of the passive voice, much of the subjunctive mood, and some participial uses. As a further revision to the Safety Rules, I ask the class to consider rewriting them in E-Prime. Table 6 gives some examples of the Safety Rules written exclusively in E-Prime.

**Readability Results •** To quantify the effect of

## TABLE 6
**Examples of Safety Rules Written in E-Prime**

1. Always wear goggles and protective footwear in the laboratory.
2. Do not wear loose clothing or jewelry near rotating equipment.

.
.
.

5. Know the location of the nearest: fire extinguisher, safety shower, exit, and first-aid supplies.

.
.

7. Label all containers with the following information: contents, concentration, date, and experimenter.

editing the Safety Rules, I assessed the three versions for readability using Writing Tools Group's Correct Grammar™ for the Macintosh,[12] a software package that checks spelling, style, and grammar. Correct Grammar and other grammar-checking software, such as Reference Software's Gram · mat´· ik® and Que Software's RightWriter® also run in the DOS environment and check for readability.

Table 7 gives the results of the readability analysis of the Safety Rules. It clearly shows that by eliminating the major contributors to the wordiness of the Safety Rules we significantly reduced the number of both sentences and words and the percent use of the passive voice. The reduction in the total number of sentences corresponds to a simple elimination

***To answer the question posed in this paper's title—writing mixes very well with safety. Our unique blending of the two has definitely enhanced our students' safety awareness.***

of irrelevant sentences. Two measures of readability, Flesch-Kincaid[13] and Gunning Fog Index,[14] show mixed results between the original and the revised documents. When we write the Rules strictly in E-Prime, however, two very interesting results occur: the passive verb tense disappears and there is a significant reduction in the educational level required to read the Safety Rules. The second result offers the true promise of E-Prime and shows it to be an economical and understandable mode of written communication that reduces fogginess. The reader cannot afford to misinterpret the intent of any technical communication that deals with critical issues such as safety procedures.

**Final Examination** • At semester's end, students take a comprehensive final examination. I include a section on writing to assess how well they can identify and suggest improvements to sentences taken from published scientific literature. Recent exam results showed that over 75% of the students could adequately identify the "agent of wordiness" and suggest significant improvements.

## CONCLUSIONS

We have created a laboratory environment where students take an active role in safety. Audit teams foster a sense of laboratory ownership because the students assume responsibility for ensuring compliance with EPA and OSHA regulations.

We have also significantly improved our students' writing skills, as witnessed by a marked improvement in their memos and reports. Using ungraded memos has proved to be an effective and efficient way to check the students' progress, and they provide meaningful and timely feedback. The memos also give students an opportunity to practice writing by forcing them to continually "distill out" the important aspects of their work and present the product in a coherent form.

To answer the question posed in this paper's title—writing mixes very well with safety. Our unique blending of the two has definitely enhanced our students' safety awareness. In addition, the safety and writing activities presented in this paper could be beneficial to any engineering discipline with a large laboratory safety component, especially if chemicals are involved.

**TABLE 7**
**Results of Readability Analysis from Correct Grammar™**

| Quantity Evaluated | Safety Document Versions: Original | Revised | E-Prime |
|---|---|---|---|
| Sentences | 22 | 16 | 15 |
| Words | 298 | 110 | 108 |
| Passive Sentences (%) | 54 | 37 | 0 |
| Flesch-Kincaid | 9.0 | 10.0 | 8.8 |
| Gunning Fog Index | 7.1 | 6.6 | 5.3 |

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# Grand Words

*Continued from page 203.*

the impurities from the final product. The final sentence, then, which states the subject of the report, appears as a logical consequence of what has come before. Indeed, we might say that it occupies the stress position of the entire paragraph itself.

Although the previous example fits quite neatly the paradigm outlined above, mere mechanical application of the "topic → verb → stress" pattern in each sentence of a paragraph cannot guarantee coherence. The author must decide, for example, whether the reader is capable of making a connection between the material in the stress position of a sentence and the topic position of the next. The link may be obvious to the writer, but if it is not clear to the reader the thread of the argument may be lost. In the example cited above, the author is writing for an audience of chemical engineers; it is taken for granted that the word "slurry" appearing in the topic position of the second sentence will be recognized by most readers as referring back to the term "aqueous phase" which appeared in the first sentence.

Up to this point we have emphasized only the author's responsibility to write coherent prose. However, just as searching for the right word forces a writer to think hard about what he really wants to say, so too can thinking about how best to structure an argument compel the writer to re-examine the logic, coherence, and clarity of what he is trying to communicate to the reader. This link between clear writing and clear thinking is a theme that we take up in the final section.

## CLEAR WRITING AND CLEAR THINKING

*Ce sont les mots qui conservent les idées et qui les transmettent, il en résulte qu'on ne peut perfectionner le langage sans perfectionner la science* ***ni la science sans le langage.*** *[emphasis added]*

A Lavoisier
*Traité élémentaire de chimie*

*(It is words that preserve and transmit ideas. As a result, we cannot perfect language without advancing science,* ***neither can we advance science without perfecting language.****)*

For most students, writing clear, precise, logical prose is never an easy task. They look upon report writing as a loose end to be tied up after the *real* (meaning *technical*) work is done. Consequently, they give little thought to technical communication. Small wonder then that student reports are frustrating to read, that they contain poorly chosen words and phrases, that ideas are haphazardly thrown down on paper. Yet, as we stated at the beginning, students *are* technically competent. They *can* develop mathematical models and simulations without knowing the distinction between the two terms. Are we being merely pedantic, therefore, by insisting upon good diction and coherently written paragraphs? Is writing ability simply a *desirable*, but not an *essential,* element of the engineer's art? We don't think so, for two reasons.

First, although student prose may be confusing, instructors can usually decipher it—but only because they supplied the topic or problem in the first place and are probably familiar with it. When students become practising engineers, however, their audience may not be so well-acquainted with the subject. Thus, not only does sloppy writing automatically place their ideas and arguments out of reach, but it can also jeopardize their careers. An engineer who writes incomprehensible prose is in danger of being passed over for promotion in favour of someone who *can* write clearly, logically, and precisely.

Second, clear thinking begets clear writing. In other words, the better we understand our subject, the better we will be able to write about it. However, careful writing can also help us clarify and understand the ideas that we grapple with. Except in those rare instances when we come to a visceral understanding of something almost immediately, most ideas and notions circulate about in our heads in a vague, half-baked form. Only when we are obliged to write them down, to explain them, and to justify them do we really force ourselves to think deeply and logically about them.

For the engineer or scientist, therefore, writing serves two purposes: to communicate our ideas to others, and, perhaps more important, to help us get those ideas straight in our own minds. Thus, we must emphasize to our students that learning how to write clear, precise prose is just as much a part of their technical education as learning how to solve differential equations. The ability to write well is an essential ingredient in developing a logical scientific argument and, as the epigraph to this section makes clear, it is therefore *fundamental* to our craft.

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# A UNIT ON ACID RAIN IN A HIGH SCHOOL OUTREACH PROGRAM

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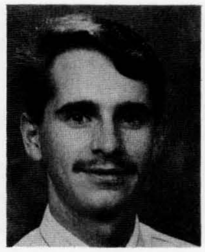

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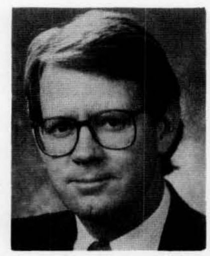

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Declining enrollment in engineering programs[1] has been a cause for concern in the educational community nationwide. To counter this downswing, engineering faculty may have to place greater emphasis on outreach programs in the future. (Bayles and Aguirre[2] described one such effort in the chemical engineering department at the University of Nevada, Reno.)

The Engineering College at the University of Wyoming has an outreach program aimed at high school science and math teachers and at high school seniors-to-be. Since many high school students are interested in environmental engineering as a career, in 1992 the Chemical Engineering Department contributed a unit on acid rain, with emphasis on chemical engineering analysis and solutions to this environmental problem. We will briefly describe the college outreach program in this article and will include details on our class dealing with acid rain.

### ESP AND HISTEP College Outreach Programs

The College of Engineering conducted outreach programs in June and July of 1992, with the help of financial support from the National Science Foundation. The June session was the Engineering Summer Program (ESP) for high school seniors-to-be, and the July session was the High School Teachers Engineering Program (HISTEP) for teachers of math, life and earth sciences, and physics. The program involved faculty from four undergraduate departments (chemical, mechanical, electrical, and civil and architectural engineering).

The goal of the ESP program was to introduce students to several of the engineering disciplines available to them on campus and to allow them to explore various career paths in engineering. They were exposed to several real-world issues through laboratory activities, computational work, and field trips, as well as through lectures and discussion.

There are many reasons why so few students are interested in engineering; the answer is not simply a lack of technical preparation in the secondary schools.[3] We felt that many school counselors and teachers do not effectively describe engineering as a career, so HISTEP was designed to show science and math teachers what engineers actually do. By giving them exposure and hands-on experience, we hoped to equip them to act as effective advocates for careers in engineering.

The three main interest areas in the ESP and HISTEP programs were

- Environmental Engineering
- Computer-Aided Engineering
- Materials Engineering

and each interest area consisted of three related subtopics. For example, in the environmental engineering area, faculty from electrical, civil, and chemical engineering discussed solar power, biological treatment, and acid rain. (The various topics for the

1992 programs are given in Table 1.) Students chose two of the three interest areas, thus covering six topics during the three-week program. A sample student schedule is given in Figure 1.

ESP participants were selected from applications which included high school transcripts, two letters of recommendation, and a 300-word statement explaining the student's interest in science and engineering. Thirty students were selected from approximately sixty-five applications from four states.

A total of twenty-three high school teachers participated in HISTEP, and they received continuing education credit for the program as well as a stipend and room and board. In addition to laboratory and discussion sessions led by the engineering faculty, the teachers participated in teaching- and learning-workshops and developed curriculum units based on their experiences in HISTEP.

## THE ACID RAIN UNIT

Acid rain is normally associated with the northeastern United States, or northern Europe, or other areas with high industrial density, particularly those areas with power plants that burn high-sulfur coal. The Rocky Mountain West is not known for acid rain,[4] although cities such as Denver and Phoenix have some acid rain and "brown cloud" problems

**TABLE 1**
**Research Topics in the Engineering Summer Program**

| Interest Area and Topics | Engineering Discipline |
|---|---|
| ***Environmental Engineering*** | |
| Acid Rain | Chemical |
| Solar Power | Electrical |
| Biological Perspectives | Civil |
| ***Computer-Aided Engineering*** | |
| NMR Image Processing | Chemical |
| Digital Electronics | Electrical |
| Electronic Materials/Manufacturing | Electrical |
| ***Materials Engineering*** | |
| Sports Dynamics | Mechanical |
| Composite Materials | Mechanical |
| Structural Engineering | Civil |

<table>
<tr><th>Time</th><th>Monday</th><th>Tuesday</th><th>Wednesday</th><th>Thursday</th><th>Friday</th></tr>
<tr><td>7:30-8:00</td><td colspan="5">Breakfast</td></tr>
<tr><td>8:30-11:30</td><td>LAB</td><td>LAB</td><td>Plant Tour</td><td>LAB</td><td>LAB</td></tr>
<tr><td>11:30-1:00</td><td colspan="5">Lunch</td></tr>
<tr><td>1:00-4:00</td><td>LAB</td><td>LAB</td><td rowspan="2">Plant Tour</td><td>LAB</td><td>LAB</td></tr>
<tr><td>4:00-5:30</td><td colspan="2">Recreation</td><td colspan="2">Recreation</td></tr>
<tr><td>5:30-6:30</td><td rowspan="2">Picnic</td><td colspan="4">Dinner</td></tr>
<tr><td>7:30-10:00</td><td>Entertainment</td><td></td><td>Entertainment</td><td></td></tr>
</table>

***Figure 1. Weekly schedule for the 1992 Engineering Summer Program***

***Activities included laboratory demonstrations and research using a water-sulfur dioxide scrubber, computer process simulations of the water-sulfur dioxide scribber, class discussions, and homework dealing with cost/risk/benefit analysis of electrical power production.***

familiar to many students. Nevertheless, the topic is pertinent for students living in this area of the country. Pedagogically, studying acid rain allowed us to explore a wide range of integrated industrial activities (such as mining, transportation, combustion, and flue-gas cleanup) associated with a very familiar and acceptable product—electricity. Wyoming is the nation's leading coal producer; most of the coal is low-sulfur and is used by electrical utilities. Some of the participants in the course had parents or spouses working in coal mining operations or in power plants, and thus they were already acquainted with the subject of air quality. Most of the students were also aware of the 1990 Clean Air Act which focused attention on electrical utilities that burn coal. In addition, the Rio de Janeiro "Earth Summit" was much in the news during the summer of 1992, and newspaper and other reports were plentiful, stimulating student interest and awareness. Thus, the participants in our program were highly motivated to explore some of the technological and societal issues associated with acid rain.

We used several methods to introduce students to the history and technology of power production and to methods of dealing with acid rain. Activities included laboratory demonstrations and research using a water-sulfur dioxide scrubber, computer process simulations of the water-sulfur dioxide scrubber, class discussions, and homework dealing with cost/risk/benefit analysis of electrical power production.

Since we wanted our unit to be more than just a technological treatment of acid rain, we also emphasized the many possibilities for work in areas related to clean-up and preservation of the environment. Additional information on chemical engineering and environmental issues was disseminated through videotapes, plant tours, department tours, newspaper clippings, and handouts. Students were asked to consider the benefits of power production as well as the societal costs and risks, and a good deal of time was devoted to roundtable discussions of these issues and the technology involved.

As can be seen from Figure 1, the unit was conducted in four three-hour days (not counting off-campus plant tours). A typical day began with forty-five to sixty minutes of class discussion, videotapes, numerical solutions to homework, and question-and-answer sessions. On the first day of class, each student was given a folder of handouts (over fifty pages) which included details of all laboratory demonstrations, blank data sheets, and calculation details. Also included were notes on the history of air pollution, several tables and charts dealing with energy production and usage, and questions designed to foster thought about cost/benefit analysis. A few newspaper clippings and magazine articles dealing with environmental issues in general were also included in this handout.

## LABORATORY ACTIVITIES

To illustrate the meaning of acidity, we introduced and discussed the pH scale on the first day of class, and to quantify the concept, we asked the students to measure the pH of several common fluids—tap and distilled water, soft drinks, vinegar, solutions of sodium bicarbonate and sodium hydroxide, and soap solutions. We used three analytical methods to measure the pH: indicator solution (Fisher Brand Universal Indicator, pH range of 4 to 12); pH papers; and a digital pH meter.

We divided the students into smaller groups to make the pH measurements. As we expected, while pH measurements using the various techniques were sometimes in good agreement, at other times they were not. Also, comparison of measurements made by using the same analytical method, but by different classes at different times, showed some discrepancies. This gave us an opportunity to talk about concepts such as precision, accuracy, reproducibility, personal technique, and use of different analytical methods. This in turn led to consideration of the all-too-familiar situation where opposing groups involved in an environmental discussion present seemingly conflicting data, analysis, and interpretation. We took this occasion to emphasize the role of the engineer in objectively gathering and reporting data.

The pH studies taught students that living things can tolerate a wide range of pH, but that chemistry, concentration, dosage, duration, and other factors are important. The discussion on experimental error and technique illustrated the difficulties involved in quantifying the level of acidification at a given location. In some cases there are little or no historical pH data, making it difficult to estimate the rate of acidification. We also cite the possibility of conflicting and erroneous measurements, and point out that all of these factors have contributed to the controversy over the rate, extent, and even the existence of damage due to acid rain.[5]

To show how sulfur oxides contribute to acid precipitation, the students used a Bunsen burner to ignite a small amount of pure sulfur held on a spatula. The burning sulfur was then inserted into the headspace of a flask partially filled with water and the Fisher indicator. As the sulfur dioxide was absorbed, there was a rapid color change from green to bright red, vividly demonstrating the acidification of water by sulfur dioxide. Repeating the experiment using a pH meter allowed a more precise measurement of pH.

We spent most of the laboratory time in operating a water/$SO_2$ scrubber (see Figure 2). This gas/liquid absorption column is constructed of plexiglas and is four feet high, three inches in diameter, and is packed with hollow glass cylinders. A compressor feeds air to the column, while $SO_2$ is supplied from a cylinder. Electronic mass flow meters and needle valves on each line allow measurement and control of the inlet gas composition. In our work, a nominal composition of two mole percent $SO_2$ in the inlet air stream was used. Tap water is fed to the top of the column with a pump, and water flow rates are measured and controlled with a rotameter and valve.

Several visual demonstrations can be made with this apparatus. Since the column is made of plexiglas, students can observe the flow of liquid over the packing. Varying gas and liquid flow rates allows them to observe both gas flooding and liquid flooding, which leads to a discussion of design and operating variables, capacity, and design for flexibility. Adding a small amount of sodium hydroxide and phenolphthalein indicator to the water in the tank makes

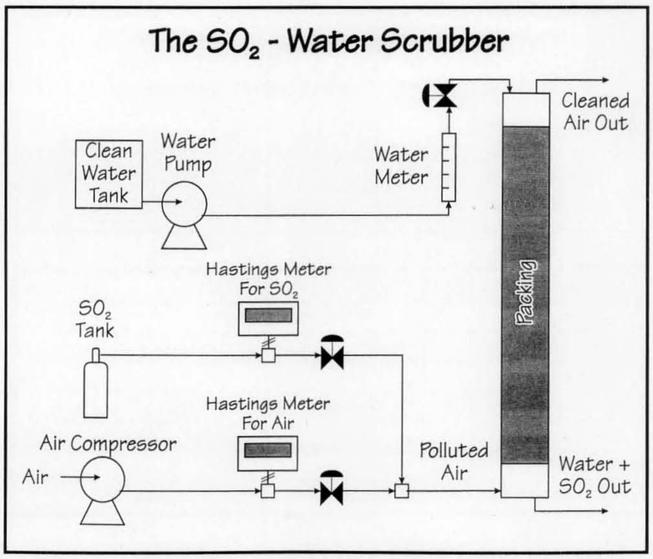


**Figure 2.** *The $SO_2$ Water Scrubber*

the inlet water bright pink. As the water flows down the column and $SO_2$ is absorbed and reacted, the pink disappears. Varying the gas and liquid flow rates causes the location of the color front to move. Students get a strong visual indication of the progress of the absorption process and see the effect of operating variables on breakthrough.

The bulk of the research, however, was done using plain tap water for scrubbing. In this work, students measured inlet gas and liquid flow rates, and titrated the outlet sample using a standard method.[6] The ideal gas law was invoked to calculate gas molar flow rates, and water volumetric flow rates were converted to molar rates using the density of water. It was then a matter of simple material balances to calculate the percentage $SO_2$ removal and subsequently to observe the effect of flow rate and inlet gas composition on the removal efficiency.

## COMPUTER ACTIVITIES

To complement the laboratory work, students were introduced to chemical process simulation using a commercial package, PRO/II (Simulation Sciences, Inc., Fullerton, CA), running on 486-based PC machines. We pointed out that our own undergraduates learn this and other simulation packages in their senior year, and that many of them subsequently use the same software in industry.

Since setting up a realistic simulation requires extensive background, we had to provide assistance to the students. PRO/II allows the user to specify column and packing type, thermodynamic model for $SO_2$ solubility, and many other options with which the students were unfamiliar, so we instead used detailed handouts to try to give them a feel for the simulator.

The purpose of the simulation was to re-create as closely as possible the experimental conditions used in the laboratory $SO_2$ scrubber. Output from the simulation included flow rate and composition of all streams, so students could calculate percentage $SO_2$ removal. It is a simple matter to adjust flow rates and re-compute stream compositions, and students had a chance to perform numerical experiments similar to the physical experiments carried out in the laboratory.

We discovered that our simulator did not agree well with laboratory results. Experimentally we observed seventy to eighty percent removal of $SO_2$ from the inlet gas, while the simulator consistently predicted removal in excess of ninety-nine percent. While this was not the desired result, it did prompt class discussion on the potential errors present in both simulation and laboratory work. Possible experimental error, inconsistent technique, and other difficulties in laboratory work became apparent to them. We were also able to point out that setting up a simulation involves many menu selections and assumptions which must be consistent with the experimental setup. Nevertheless, the students could see clearly the iterative process that many practicing chemical engineers must use in the design process: laboratory experimentation over a specified set of operating variables, followed by numerical simulation, followed by careful error analysis and comparison of experiment and simulation, followed by an improved set of experiments.

## OTHER ACTIVITIES

We spent most of the time either in the classroom or the laboratory, but for broader exposure we also included several other activities (see Figure 1). ESP students took several field trips, including an all-day trip to a near-by power plant and a coal mine where they were exposed to many of the activities and unit operations associated with electrical power production: open-pit strip mining, land reclamation, rail transportation, solids handling, combustion, steam generation, electrical turbines, cooling towers, scrubbers, electrostatic precipitators, and ancillary control and monitoring equipment.

HISTEP participants were geared more toward curriculum development, so they spent at least an hour each day on teaching methodologies and on developing course plans which incorporated the HISTEP subjects into their classroom instruction. These curriculum activities were coordinated by the Wyoming Center for Teaching and Learning. The teachers were evaluated on the basis of their course plans and received continuing education credit for their participation in the program.

We made extensive use of videotapes during the four-day session. They were not exclusively on acid rain, but were chosen to given the students a broader exposure to issues and possible career paths in chemical engineering.[7] We also showed a department videotape on chemical engineering careers which we use in high school recruiting efforts and gave each of the participants a copy of the tape for later use at their respective schools.

Much of the acid rain unit dealt with experimental chemistry and engineering. While most of the high school teachers found this interesting from a personal standpoint, those whose teaching specialty was mathematics had difficulty finding material to take back to their classrooms. All HISTEP participants had been presented with a student version of TKSolver (Universal Technical systems, Rockford, IL). Therefore we presented the math teachers with an extra problem dealing with the environmental effects of paper and plastic grocery sacks, using a discussion recently presented by Allen and Bakshani.[8] This problem was explored using TKSolver in List Solve mode.

## DISCUSSION

Both ESP and the HISTEP classes were run in a very informal atmosphere, and we had ample opportunity to ask the students what they were learning, what they enjoyed, and what they did not like. In addition, a brief, anonymous class evaluation form was filled out by each student at the conclusion of the unit. In this section, we will describe student reactions to the unit and will pass on our impressions of the successes and failures of the program.

Regens and Rycroft[5] present some interesting history of air pollution (see Table 2). Our students were interested to learn, for instance, that air pollution was a problem in imperial Rome, that smoke from wood and coal has been a problem for centuries in Great Britain, and that King Henry once issued an edict calling for decapitation of any who were found "guilty" of burning coal.

An early example of completely misguided government legislation in this area came in 1834, when the British Parliament enacted laws requiring that locomotives must consume their own smoke. (Our students immediately sensed something amiss with this law!) This particular bit of history gave us a good opening for a discussion on the principle of mass conservation and led to the first law of thermodynamics as well.

Because environmental issues are in the news daily, we deliberately tried to provoke class discussion about acid rain and other topics such as recycling, nuclear waste storage, land reclamation, and economic impact of environmental regulation. The "Earth Summit" of 1992 led to a call for holding $CO_2$ emissions at 1992 levels, so we asked the students what conveniences they would be willing to give up to help meet this goal. Not surprisingly, the "sacrifices" they volunteered were minimal (toaster ovens, curling irons, etc.). The follow-up question, however, did provoke considerable interest and discussion. The question was, "*When* would you be willing to give up the items?" A few altruistic people argued for voluntary conservation, while others said, in effect, "We will conserve when the government forces us to." A third group seemed content to wait for Armageddon. The high school teachers pointed out that when the price of electricity became too high, people would voluntarily reduce consumption (the law of supply and demand, *and* pricing). We considered this sort of discussion to be important because it put some laudable but abstract environmental goals (conserve, reduce) on a very personal basis for the students.

In reviewing the written comments, most students made no mention, pro or con, regarding the class discussions. We estimate that ninety percent of the students actively participated in the discussions, however, and they seemed to enjoy it. Indeed, among the high school teachers it usually required an effort to terminate class discussion and move them on to the laboratory.

All students enjoyed the hands-on demonstrations and operation of the scrubber, and most of them listed laboratory activities as their favorite part of the course. It was usually a matter of showing them the basics and then getting out of their way. The mathematics teachers were the exception: while they

**TABLE 2**
**Some History of Air Pollution**

- A.D. 61: Senaca (Roman philosopher) wrote of Rome's polluted vistas:
  *As soon as I had gotten out of the heavy air of Rome and from the stink of the smoke chimneys thereof, which, being stirred, poured forth whatever pestilential vapors and soot they had enclosed in them, I felt an alteration of my disposition.*
- A.D. 1060: Eleanor of Aquitaine, wife of King Henry II of England, moved from Tutbury Castle in Nottingham because of the pollution of wood smoke.
- A.D. 1273: English royalty issued decrees barring the burning of coal in London. The effort was futile, because with the depletion of forests in England (and lack of firewood) people increasingly turned to coal.
  *Be it known to all within the sound of my voice, whosoever shall be found guilty of burning coal shall suffer the loss of his head. (King Edward I, ca. 1300)*
- A.D. 1578: Elizabeth I is annoyed by coal smoke and complains to Parliament. Coal burning is banned while Parliament is in session.
- A.D. 1661: John Evelyn wrote, "Fumifugium, or the Inconvenience of Aer and Smoak of London Dissipated (together with some Remedies Humbly Proposed)."
- 1772: Second edition of Evelyn's book is published.
- 1819 and afterward: British Parliament issued pollution abatement decrees. Scrubber technology was developed in 19th century. In 1845, Parliament passed a law requiring locomotives to consume their own smoke.
- 1952: A dense fog blanketed London from December 5-8. Fog, mixed with polluted air, caused an estimated four thousand deaths from emphysema, bronchitis, and cardiovascular problems. This led to Britain's first modern clean air legislation.

enjoyed the experiments personally, they expressed concern about the practicality of transferring the hands-on work to their own classrooms.

The booklet of supporting information seemed to be of special value to the high school teachers. Converting the laboratory readings into data for mass balance calculations involved simple algebra, some reaction stoichiometry, ideal gas laws, and knowledge of fluid properties. In addition, we provided a few word problems related to fuel, ash handling, and shipping requirements for a coal-fired power plant. The paper versus plastic bags problem of Allen and Bakshani[8] was also very popular. The teachers appreciated this real-world data and felt that their students would enjoy working on such problems. We believe we were successful in providing some mathematical problems that could be used in high school mathematics, physics, or chemistry classes.

An area that needed more time, according to the students, was computer modeling of the $SO_2$ absorption process. They would have preferred an opportunity to try the various menu options and run more cases. In retrospect, we see the need for more time to experiment with the computer and to answer questions about its operation.

Another feature of the course that did not go over as well as anticipated was the videotapes. Both high school students and teachers indicated that there were too many videos and that some of them ran too long. We expected that the adults might grow restless watching videotapes, but we were surprised (and rather pleased) to find that high school kids, too, preferred hands-on work to passive viewing.

Our department videotape did generate interest, however—particularly among the teachers. We provided each of them with a copy of the tape to take home, and they indicated they would show it in their classes as a way to introduce students to the field of chemical engineering in general and to our department in particular.

## CONCLUSIONS

Judging from the students' verbal and written comments, we believe the unit was a success. Linking chemical engineering principles and practice to an environmental problem proved to be very effective in capturing their interest. The operation of the scrubber, analytical wet chemistry, and lab demonstrations gave a hands-on experience that all of them enjoyed. We were able to bring a strong element of personal and societal values into the discussion, as well as a discussion of technical issues. This helped students appreciate the potential that chemical engineers have to design and develop useful solutions to problems of public interest and concern. The value of the engineer as a literate and articulate advocate for the profession was stressed.

We entered the project with some trepidation. We are accustomed to dealing with students whose chemistry, physics, mathematics, and engineering skills are more developed. In addition, college-age students well into their major are typically motivated by other factors, such as a desire for good grades, fear of failure, desire for a good job, and protecting their large investment of money and time. Our only hold on the participants in this program was to make the course genuinely interesting and challenging.

While we feel that this course was a success, only time will tell if we have achieved our goal of increasing the number of students interested in chemical engineering as a career. We hope to monitor incoming freshmen and transfer students in the future to see if any graduates of ESP join our undergraduate program. Similarly, we hope to find out if high school teachers have been helped in describing chemical engineering careers to their students. In the meantime, we will continue with this and other outreach efforts.

## ACKNOWLEDGMENTS

This program was supported by NSF Grant #TPE-9055487 and #RCD-9154885. Sally Steadman, Department of Mechanical Engineering, was coordinator of the ESP and HISTEP programs. David Cooney, Chemical Engineering, provided assistance in the $SO_2$ scrubber exercises.

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ChE classroom

# COMPUTING TEACHING WITH FORTRAN 90


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Fortran 77 is taught in chemical engineering departments throughout the world and is the center of all scientific and engineering computing. Fortran was developed by John Backus of IBM and has passed through a number of stages including Fortran 66 and in 1978 to the then-new standard Fortran 77. ANSI and the International Standards Organisation (ISO) began work on a new standard for completion in 1982 and in 1991 introduced ISO/IEC 1539: 1991. This new standard is Fortran 90.

What teaching changes will be involved for computing with Fortran 90? This question will undoubtedly be of primary concern to chemical engineering departments during the next few years. The first element to be considered is that everything written in Fortran 77 will be fully compatible with Fortran 90. It will be possible to make no teaching changes and to simply call on a new compiler, f90. But a department that follows this policy will miss out on all of the advantages developed over a decade of work by experts in Fortran compilers. The advantages make use of the best features of other languages so that a robust and reliable software code can be written.

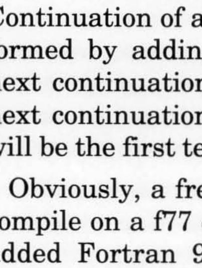
The intent of this paper is not to list all of the Fortran 90 features but instead to simply introduce it and give the reader an idea of the nature of the new programs. Most of these new programs will not look like Fortran 77 programs. The selection of the programs presented in this paper will demonstrate what Fortran 90 is all about.

One of the introductory topics discussed in the teaching of Fortran 77 is the requirement that Fortran statements lie between columns 7 and 72. Comments start with a C in column 1 and continuation lines with a character such as + in column 6, with statement numbers in columns 1 to 5. This is called fixed format Fortran and can be compiled with one option of the Fortran 90 compiler. But this fixed format is now considered obsolete and instead, programs can now be written in free format. This makes teaching much easier.

With free format, Fortran 90 programs can start in column 1 or any column through 132. There is no need for indentation at the start of a Fortran line, although this is often done for readability. Comments begin with an exclamation mark (`!`) which can be in any column. Comments can be added after a Fortran statement by `!`, followed by the comments. Continuation of a long Fortran 90 statement is performed by adding an ampersand (`&`) to start the next continuation line, and then an `&` to start the next continuation line. This change to a free form will be the first teaching change for Fortran 90.

Obviously, a free format form of Fortran will not compile on a f77 compiler, so this begins the use of added Fortran 90 features that require the f90 compiler. It should be noted that the word obsolete was used above—a number of Fortran 77 statements are not recommended as they are considered obsolete. This recommendation leads to robust and reliable code.

Teaching Fortran 77 led to difficult statements like COMMON and BLOCK COMMON which were useful in transferring information from a main program to subroutines, or from subroutine to subroutine. But neither of the COMMON forms are recommended in Fortran 90. How can a Fortran 90 pro-



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gram operate without a COMMON statement? It has a new feature, called the module. It removes any doubts on program reliability that originated in the COMMON statement.

Teaching changes may be progressive from giving the full COMMON details in a Fortran 77 course to giving no details at all in a Fortran 90 course. The object of this teaching change concerns thinking about robust and reliable code while writing the code.

Other Fortran 77 statements that have become obsolete include DOUBLE PRECISION, computed GO TO, and arithmetic IF statements, to mention a few. Teachers of computing in chemical engineering who are aware of these statements will need to know the new replacements statements in Fortran 90.

A better approach to teaching Fortran 90 is to present it as a new language with a wide range of new features and statements. It covers a wider range of features than Fortran 77, introducing structures, pointers, arrays, and procedures, and can process character strings and bits of information. Its vocabulary is well defined and includes what at first glance looks like unusual expressions, such as "structure constructor." (Further details on Fortran 90 can be found in Metcalf and Reid.[1]) The following are a few simple free format Fortran 90 programs, presented to provide a flavor of Fortran 90 to the reader.

### FORTRAN 90 EXAMPLES

#### Example 1

Example 1 is shown below and includes the program and end program statements. Note how the program name, example 1, assists in locating the full extent of the main program.

```
program example_1
print *, 'This is the output from example_1'
stop
end program example_1
```

The output from this program is given by

```
This is the output from example_1
```

#### Example 2

Example 2 is a Fortran 90 program that no longer looks like a Fortran 77 program. Its function is to demonstrate some features, including high precision calculations and derived data types. Real variables can be calculated with at least 10 decimal places by the definition of an integer parameter r10, shown on line 2. Real variables such as sum, c, and d in the program carry the "r10" notation, giving

***What teaching changes will be involved for computing with Fortran 90? . . . The first element to be considered is that everything written in Fortran 77 will be fully compatible with Fortran 90.***

these variables 10-figure precision. It is possible to define other data types that have components. These structures can be complex, but a simple example is given of a type called university. It has three components with data types: character, real, and integer. It is bounded by the end type university statement. The variables nsw and queens are defined to be of type university and each will have three components.

```
program example_2
integer, parameter    :: r10=selected_real_kind(10)
real (kind=r10) sum, total, c, d, e
integer difference
  type university
      character (len=30) name
      real engineering_depts
      integer academic_numbers
  end type university
      type (university) nsw
      type (university) queens
! simple examples follow
   sum= 1.23456789_r10
   total=sum**2
!
   c=1.0_r10
   d=3.0_r10
   e=c/d
!
write (*,*)'Kind=R10 Variables SUM=', sum
write (*,*)'TOTAL=', total
write (*,*)'    E=', e
!
  nsw = university ('University of NSW', 8, 150)
  queens = university ('University of Queensland', 6, 120)
  difference = nsw%academic_numbers-queens%academic_numbers
!
write (*,*)'Difference in Academic Numbers=', difference
!
  stop
end program example_2
```

The output from Example 2 is given by

```
Kind=R10 Variables  SUM=  1.2345678899999999
TOTAL=  1.5241578750190519
    E=  0.3333333333333333
Difference in Academic Numbers= 30
```

The precision of the output should be carefully noted. Example 2 continues with the structure constructors for the type university variables nsw and queens. This input of information includes the "name" of the university, the number of "engineering_depts," and the "academic_numbers" in all departments. The difference between the "academic_numbers" at nsw and queens is given by the variable difference. The output shown above is of course only as accurate as the information in the structure constructors.

*Example 3*

Example 3 is similar to Example 2 but demonstrates the use of procedures. The program consists of three parts: the main program "example_3," a module called type maker, and a subroutine called calculation. Each part may be separately compiled and the object code linked for execution. The main program contains the statements

```
use type_maker
external calculation
call calculation
call write_result
```

The main program listing is

```
program example_3
  use type_maker
  external calculation
  integer, parameter :: r10=selected_real_kind(10)
  real (kind=r10) sum, total, c, d, e
  integer difference
    type (university) nsw
    type (university) queens
!
!simple examples follow
!
  sum=1.23456789_r10
  c=1.0_r10
  d=3.0_r10
    call calculation ( sum, total, c,d,e)
!
  write(*,*)'Kind=R10 Variables SUM=', sum
  write(*,*)'TOTAL=', total
  write(*,*)'    E=', e
    nsw= university('University of NSW', 8, 150)
    queens=university('University of Queensland', 6, 120)
    difference=nsw%academic_numbers-queens%acadedmic_numbers
    call write_result (difference)
  stop
end program example_3
```

Modules are a very important feature of Fortran 90. They can be used by the main program and subroutines to access information (such as the definition of the type university) that more than one of them needs.

```
MODULE TYPE_MAKER
  type university
    character (len=30) name
    real engineering_depts
    integer academic_numbers
  end type university
contains
  subroutine write_result (number)
  integer, intent (in) :: number
  write (*,*)'Difference in Academic Numbers=', number
  end subroutine write_result
END MODULE TYPE_MAKER
```

Modules are procedures that can also contain subprograms such as the subroutine write result. Note that the module is named type maker and ends with end module type maker. An example of an external subroutine is given by the subroutine calculation.

```
subroutine calculation (a, b, c, d, e)
integer , parameter :: r10=selected_real_kind(10)
real ( kind=r10), intent (in) :: a,c,d
real ( kind=r10), intent (out):: b,e
      b=a**2
      e=c/d
end subroutine calculation
```

The subroutine arguments a, b, c, d, and e are of kind, r10, that is of at least 10-figure precision. Fortran 90 also uses the attributes, intent (in) and intent (out), to be used to specify the input and output arguments to the subroutine. The output from Example 3 is identical with the output from Example 2.

*Example 4*

Example 4 shows some of the powerful features of Fortran 90: pointers, targets, automatic arrays, do loops, and matrix multiplication.

```
program example_4
  real, pointer  :: finger
  real, target   :: a,b
  real, dimension ( : , : ), allocatable :: matrix_a, matrix_b
  real, dimension ( : , : ), allocatable :: matrix_c
  integer n
  a=1.0 ; b=2.0 ; n=5 !n could be entered by read (*,*)n
  allocate ( matrix_a(n , n), matrix_b(n , n) , matrix_c(n , n) )
j_loop :     do j=1, n
k_loop :     do k=1, n
      matrix_a(j,k)=real(j)*real(k)
      matrix_b(j,k)=matrix a(j,k)
        if(matrix_b(j,k) <= 10.0 ) cycle
      matrix_b(j,k)=matrix_b(j,k) + sqrt(0.5)
    end do k_loop
    end do j_loop
  matrix_c=matmul(matrix_a, matrix_b)
    finger=>b
      if(n==1) finger => a
  write(*,*) 'Example_4  Finger=', finger
  stop
end program example_4
```

A real variable, "finger," is given pointer attributes by its definition. A pointer points to a target and real variables, "a,b," are given target attributes. They are a new and powerful feature of Fortran 90, particularly useful in operating on linked lists such as an adapted refined grid. Their use in engineering may not immediately appear to be obvious, but a simple example is shown as part of Example 4.

Arrays in Fortran 90 can have fixed bounds such as a(10), but only a section of the array can be used with the colon ( : ) notation, such as "a( 5 : 10 )." A two-dimensional array with initially unspecified lower and upper bounds is given by matrix a ( : , : ). These bounds can be allocated during execution, making for greater flexibility. Example 4 shows three arrays: matrix_a, matrix_b, and matrix_c, with the attribute allocatable. An integer n that is given the value 5 in Example 4 could have been read in and could take on a wide range of integer values. The allocate statement then allocates the required amount of memory for these arrays.

Do loops are considerably different in Fortran 90 and may include no labels. They start with a do statement and end with an end do statement. Each loop may be given a name, such as "j_loop," which assists in locating the limits of a particular loop. There are no statement numbers in the recommended form of the do loop, the final statement being the end do statement. The cycle instruction permits a direct jump to the end do statement and the exit statement permits a direct exit from the loop.

Fortran 90 permits direct matrix multiplication through the "matmul" statement. Other matrix operations are standard in Fortran 90.

The statement

```
finger => b
```

shows the pointer finger is pointing at the target b. The next statement contains the logical equal comparator, and if it is satisfied

```
finger => a
```

The output from Example 4 is given by

```
Example_4        Finger=     2.0000000
```

## SUPERCOMPUTERS

Fortran 90 could well be the new world standard in computing until the year 2000. Fortran 90 compilers can exploit the advanced architecture of parallel processors or supercomputers. It might be expected that desktop supercomputers will lead to considerable advances in engineering, particularly in finite element methods and computational fluid mechanics. It might also be expected that the obsolete and archaic features of some parts of Fortran 77 (such as the arithemetic IF statements, some DO statements, and the H edit descriptor) will be removed in later versions of Fortran 90. Fortran 90 statements can begin in column 1, thus removing the obsolete card image concept in Fortran 77. One of the important advances of Fortran 90 is the availability of instructions that give a good methodology in program design. This can lead to both robustness and an error-free code, which can be fully exploited on supercomputers.

## CONCLUSIONS

Engineers will need to spend some time learning the new features of Fortran 90 if they wish to undergo the conversion from Fortran 77. A program written in Fortran 90 may not look like a Fortran 77 program because of the many new features of Fortran 90, and many obsolete features of Fortran 77 should no longer be used. The only Fortran 90 compiler available from NAG provides reasonable error messages during compiling, which is an improvement over Fortran 77. In some cases the error messages even identify a line number and print a part of the statement that contains the error. Also, the compiler lists undefined variables. Error messages during execution are good and, for example, provide the dimensions of matrices if they do not compute.

One of the most important advantages of Fortran 90 will be the portability of code. A large number of software products such as mathematical subroutines and graphical packages will be rewritten in Fortran 90 to provide good interfaces.

This article makes no attempt to list all the statements and features of Fortran 90, as it is an extensive and powerful new language. There can be no doubt that it will have an important impact on the engineering profession for a number of years to come.


## ACKNOWLEDGMENT

Comments by John Reid of the Rutherford Lab, England, were most welcome.


## REFERENCES


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# REVIEW: *Plastics Recycling*

*Continued from page 199.*

rapidly changing field, however, some of the information in this book is already dated. Advances in recycling have produced better processes which allow recycled plastics with specifications (much like virgin plastics) to be produced, particularly by companies like Union Carbide, Dow, Mobil, Quantum, and Waste Alternatives. These improvements in processes and products have inevitably led to the demise of several small companies—especially in the plastic lumber area. Many large companies, however, (such as Mobil and Amoco) have entered the field with more efficient processes and better quality control.

A more recent book, published by the American Chemical Society, ACS Symposium Series 513, *Emerging Technologies in Plastics Recycling,* (1992), is also becoming dated, but has significantly more scientific data. Clearly, plastics recycling is a dynamic area of research and business, and continued developments are in progress. This book provides an excellent starting point for those who are interested in plastics recycling. ❐

ChE classroom

# SIMULATION IN THE CHEMICAL ENGINEERING CLASSROOM

WALLACE B. WHITING
*West Virginia University*
*Morgantown, WV 26506-6101*

Many educators have found that active learning strategies can help students develop the higher level thinking skills of analysis, synthesis, and evaluation that are the essence of engineering.[1,2] Simulation is an effective technique for creating a classroom environment that is conducive to such learning. Whether we simulate a process on a computer or the work of an engineering team in a design project, the simulation experience brings a sense of reality to an assignment.[3,4] Students become more active, more interested. Few faculty who have engaged their students in simulation doubt its effectiveness.

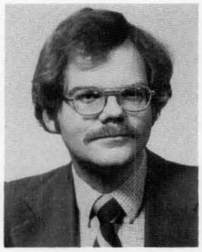
Can we use simulation in all our courses? Should we? Through the following examples, I hope to show that the answer to both of these questions is "yes."

## ROOT-FINDING ALGORITHMS

On the first day of a course in numerical methods for chemical engineers, I break the class into small groups of three to five students, and each group is told to find the largest positive real root of a function. The students don't know, however, that each group is given the *same* function, but in a *different* form. One group must find the solution by querying a computer program set up on a PC that accepts their guess and gives a value of the function, while another group is given an algebraic form of the function, which is a cubic. A third group is given a different form of the function, and yet another group is given the problem behind the assignment: to solve the van der Waals equation for the vapor molar volume given the constants a and b, the temperature, and the pressure. Each group is told to find the solution to the problem and to carefully keep track of how they solved it so that they can explain their technique to the rest of the class.

***Can we use simulation in all our courses? Should we? Through the following examples, I hope to show that the answer to both of these questions is "yes."***





**Wallace B. Whiting**, *P.E., is Associate Professor of chemical engineering at West Virginia University, where he has taught for the past decade. He is active in ASEE and AIChE, and his research and teaching interests range from thermodynamics to process safety and process design. He welcomes dialogue on this and all of his articles.*

The results of this exercise are amazing. My sophomore students (who have had no previous courses in numerical methods) independently develop all the root-finding algorithms in the text within thirty minutes, in addition to some other more sophisticated algorithms. (It should be noted that while the students have all brought the text to class, usually none of them has opened it yet!) As the groups go to the front of the class to explain their techniques, I tell them that this is called the bisection method, or Newton's method, or resubstitution with acceleration, or brute-force, or whatever. We discuss such topics as error propagation, accuracy criteria, advantages of solving the function analytically (for the groups that have the analytic form of the function), strategies for developing a good initial guess, and the risks and benefits of using a method that has already been programmed. Our discussion invariably broadens to include the roles of textbooks, computers, their own physical understanding, and their colleagues in solving numerical problems. We talk about why they are taking the course and what its relationship is to the rest of the curriculum and to their future careers.

Simulation? Yes, we simulated an engineer's attempt to solve a numerical (in this case, thermodynamics) problem. The students had a wide variety of experiences (guaranteed by the different versions of the problem) which they shared with each other in a structured way.

Through simulation the students develop new strategies for solving numerical problems. They learn quite a bit about specific numerical techniques (more than they could have learned in one traditional lecture), and they gain confidence in their abilities to solve new classes of problems. Perhaps most important—they learn the connection between numerical methods and the rest of chemical engineering. And, of course, they learn some thermo.

For larger classes, I use more groups rather than larger ones, and I choose one group of each type to lead the class discussion. If discussion lags (which is rare), another group is asked how its approach differed.

I have used the same kind of exercise with an optimization problem, with similar results.

## THE LEVEE PROBLEM

I have used the "levee problem" several times—in senior design courses at two different universities and at a conference where most of the participants were chemical engineering faculty.[5] The kernel of the simulation comes from a homework problem, the source of which has been lost over the years. As originally stated, the problem appears to be a single-answer economics problem in which the student compares building a flood-control levee to not building it. Students are given a scenario in an expanded version of the problem (see Figure 1). They must write a memo, detailing their recommendations, to a specific person who has a specific technical background.

Responses to the assignment are wide ranging. Some students focus solely on the economics, concluding that the levee is a terrible alternative. Others ignore the costs and make what they feel to be the ethically correct recommendation (to build the levee at any cost). Many other solutions are presented, but few students attempt to tie the various aspects of the problem together.

***But, what have they learned? . . . They knew what to do next; they knew how to learn on their own; they gave themselves the next assignment; they were good problem solvers. Heady stuff. And they learned that statistics can be useful— all within the confines of one class period.***

### PART 1
#### *Memo and Feedback*

In class, the students are paired and asked to play the role of Chris E. Smyth as they read each other's memos. Chris is a very busy executive who has only three minutes to read the memo and to answer the following three feedback questions: (1) What is the recommendation? (2) Do you trust (or believe) the recommendation? (3) What will you do next? The students give immediate

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**TO:** Workshop Participants
**FROM:** W.B. Whiting, Vice President of Engineering WBW
**DATE:** 18 October 1990
**SUBJECT:** Economics Revisited
**CC:**

Please submit your answer to the following problem by noon, Wednesday, October 24, 1990. Someone will be chosen to present the problem to the group at 1:30 P.M., Thursday, October 25, in Room 449.

In your position as Director of Investment Planning at Technocats, you must make a specific recommendation for or against the capital expenditure described below. Write a memo to your boss, Chris E. Smyth, Executive Vice President, recommending and justifying appropriate action.

After a chemical plant was built on an island in a river, our geology/hydrology department discovered that the island was occasionally under water. U.S. Army Corps of Engineers data indicate that the chances of a flood are about one in seven each year. The likely flood damage would be $250,000, and we would need to lay off ten employees for three months during the repair, which would be a boon for a local construction firm.

A protective levee would cost $600,000 (total fixed capital investment), and our civil engineering department estimates its useful life as 28 years, with no salvage value. Our economics group has worked up an opportunity cost of 10% per annum, based on after-tax cash flows and no inflation. Other economic data are given below.

Remember, your boss is a former geologist who doesn't know much about time value of money, discounting, annuities, etc.

- Fixed costs other than maintenance: negligible
- Annual maintenance cost: 1% of fixed capital investment
- Effective income tax rate: 48%
- Depreciation: AMACRS, 15-year class life (ignore mid-year convention)
- Working capital: none
- Use end-of-year annualized costs.

***Figure 1. Levee problem assignment memorandum***

feedback to each other by answering these questions.

We then discuss the responses. With some classes I have already brought in engineering ethics, but with others I have not. Regardless of their background, however, the intensity of the discussion is always high.

### PART 2
### Engineering Presentation

The students are formed into small groups, and each group is given a role to play in the ensuing simulation (see Figure 2). The students are given fifteen to twenty minutes for preparation before the simulation begins. One member of a "Director of Investment Planning" group is chosen to present the results and recommendations to the vice president, chosen from a "Chris E. Smyth" group. Some groups prepare extensive overhead transparencies or "chalk talks," while others develop note cards or lists of questions. As before, more than one group may be given the task of preparing the Chris E. Smyth role, but only one member from one group is chosen for the simulation in front of the class. Thus, all students actively prepare for the simulation and all have an interest in the outcome, even though only one student will ultimately play the role. The other group members are anxious to see how their strategy works, and the groups that are not chosen have an opportunity later to compare their strategies to the ones demonstrated.

During the preparation time, no group knows what the other groups have been told. In particular, Chris E. Smyth and the Director of Investment Planning have no idea what will happen next. As a reporter enters the scene, with tape recorder running, the simulation heats up, and what you fear will happen usually does. The engineer talks to the reporter as if the reporter were an engineer, or an idiot. Outrageous one-liners (sound bites) are uttered. The reporter has a field day. Sometimes Chris E. Smyth brings things back under control, and sometimes not. You never know what is going to happen.

Next an observer group leads the class discussion. I initiate the first topic: *Why are we doing this?* Although they come up with various responses, none of the students has ever indicated any concern that time was wasted in this simulation exercise. They all know that it

**Chris E. Smyth**

You are the Executive Vice President of Technocats, Inc. As indicated on the assignment memorandum, you are a former geologist (not a chemical engineer) who doesn't know much about time value of money, discounting, annuities, etc. However, you are a good manager and have risen through the ranks at Technocats because of your ability to deal with people and to get things done. The Director of Investment Planning reports to you, and you really need to know what to do about this levee/flooding situation. You will make the final decision, but you will need to justify it to the President, to the CEO, and, perhaps, to the Board of Directors.

We have simulated your office, complete with desk, phone, etc. The Director of Investment Planning will come to your office to make a presentation.

**Director of Investment Planning**

You are a chemical engineer. As indicated in the assignment memorandum, you must make a specific recommendation for or against the capital expenditure described. You will go to Chris Smyth's office and give a presentation (you are expected). Chris will make the final decision, but you and your group have done all the analysis. Remember the background of Chris Smyth while preparing your presentation. You will have only about 5 minutes for the presentation.

**Reporter**

Neither Chris Smyth nor the Director of Investment Planning knows that you will show up. You are an investigative reporter for the *Washington Post.* You have heard a rumor that Technocats has a chemical plant that could be subject to a flood. As with most journalists, you have no scientific or engineering training, but you are bright and ambitious. You go to see Chris Smyth, Executive Vice President, without an appointment. You have a tape recorder to record everything. During the simulation, you will be announced by the secretary, but, before Chris has a chance to say no, you enter the office and begin asking questions.

**Observer**

Your job is to observe what is going on. The Director of Investment Planning will give a presentation to Chris Smyth (Executive Vice President). During the presentation, an investigative reporter from the *Washington Post* will show up and begin asking questions. Neither Chris nor the Director of Investment Planning has any idea that the reporter exists.

After the simulation, you will be called upon to give an analysis of the simulation and to lead the postmortem.

***Figure 2.*** *Roles for the levee problem simulation*

can happen to them. They realize that the engineer's inability to say the "right things" to the reporter stems from the engineer's overly simplified analysis of the situation and a lack of understanding of the difference between engineers and the rest of the population which they serve. The ensuing discussion ranges from topics such as ethics, to net present value, to statistics.

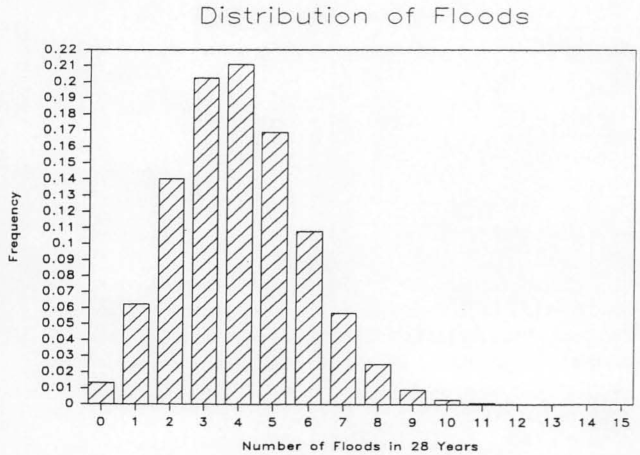


***Figure 3.** Distribution of floods*

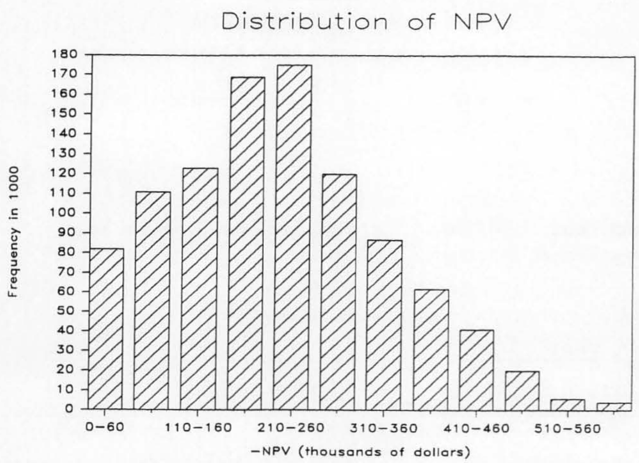


***Figure 4.** Distribution of net present value*

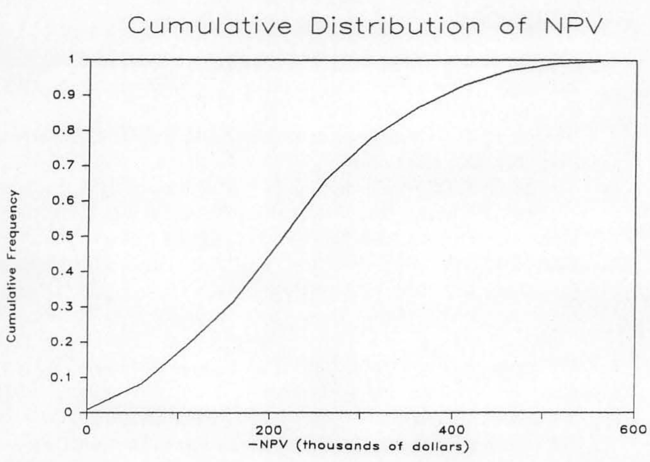


***Figure 5.** Cumulative distribution of net present value*

## *PART 3*
### *Monte Carlo Simulation*

Yes, *statistics.* Students typically assume, for their calculations, that the interval between floods is exactly seven years. Some students assume that the first flood is in the first year while others assume that it occurs in the seventh year. The first time I used this simulation, my students asked how to quantify the chances that there would be a given number of floods in a given number of years and how the timing of such floods would affect the economics. They realized that they couldn't integrate the societal, technical, and financial aspects of the problem without such data. The *students* developed the next assignment: to do a Monte Carlo simulation to determine the frequency distribution of floods and the frequency distribution of the net-present-value comparison (essentially a probabilistic benefit-cost analysis[6]). Most of these students had taken no courses in probability or statistics, and none of them had heard of Monte Carlo simulation when I told them that that was what they were describing. Most students chose to use LOTUS 1-2-3 for the Monte Carlo simulation, but some wrote BASIC or FORTRAN programs. The results of their simulations are shown in Figures 3, 4, and 5. The same thing has happened with succeeding classes.

But, what have they learned? After years of diligently studying for what they *hoped* would be a rewarding career, they now know it's real. What engineers do is important (and difficult and scary). They are preparing for their career, and they know it. Realizing that their calculations can affect real people in serious ways is exciting. They knew what to do next; they knew how to learn on their own; they gave themselves the next assignment; they were good problem solvers. Heady stuff. And they learned that statistics can be useful—all within the confines of one class period.

But who was simulating what? The students were simulating a common engineering situation wherein after analysis, synthesis, and evaluation the engineer presents and defends a recommendation to technical and non-technical audiences, receives criticism, and decides what to do next.

For ease of use in different classroom settings, I have broken this levee problem simulation into three parts. The memo and feedback portion of the problem (Part 1) can be used to introduce students to simulation. The engineering presentation (Part 2) can be used with or without the reporter, or the full simulation, including the Monte Carlo assignment (Part 3) can be used. In each case, a postmortem discussion of the simulation, bringing in as many student viewpoints as possible, is essential.

## OTHER SIMULATIONS

There are many other types of simulations, ranging from intricate ones to simple ones. At West Virginia University we have used an extended and involved simulation for the year-long senior design project for over fifty years.[4] An AIChE Student Contest Problem can also be adapted for individual or group simulation. A very simple simulation which I have used to introduce a guest lecturer in a course is shown in Figure 6. At first glance, it appears that nothing has changed. I have merely let the students know the topic for two lectures while I am out of town. The subtle simulation here introduces the students to the concept of professional development activities and to the role of government regulation in their profession. Their attitudes toward the lectures are modified, and their learning is enhanced.

I have sometimes videotaped more intricate simulations, with the class viewing and analyzing the simulation during the postmortem. Additional faculty, graduate students, and others (including our outside seminar speakers) are sometimes brought in to participate.

***Technocats Inc.***

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Los Angeles, CA 90024-1592

**TO:** Task Force 108A
**FROM:** W.B. Whiting, Vice President of Engineering
**DATE:** 26 February 1992
**SUBJECT:** Safety
**CC:**

Please read the attached article from the *Los Angeles Times* concerning new OSHA regulations. To prepare for these regulations, it is imperative that all Technocats engineers attend a special Professional Development Seminar on Monday, March 2, and Wednesday, March 4, 8:00—9:50 A.M., in Room 2444 of our headquarters. We have arranged for an outside expert in HAZOP (HAZard and OPerability study) to present these seminars. For Friday, March 6, you will perform a HAZOP on the reactor of our subsidiary XXX's Acrylic Acid Plant.

Our research department has found the attached article from *Plant Operations Progress* that should be of interest.

Attachments:

*Los Angeles Times,* "OSHA Issues Safety Rules to Avert Explosions at Petrochemical Plants," February 15, 1992, p. A5.

Kurland, J.J., and D.R. Bryant, "Shipboard Polymerization of Acrylic Acid," *Plant/Operations Progress,* **6**(4), 203 (1987).

***Figure 6.*** *Announcement of guest lecturer*

Design projects and laboratory experiments can easily be developed as simulations, but a good homework problem from any engineering course can be put into a real context. After preparation, students role-play the situation. Finally, class discussion can help students explore and understand the important relationships both within the subject matter and between it and the bigger picture.

## CONCLUSIONS

Simulation is an ideal technique for improving student learning. These activities help students recognize connections between courses, the curriculum, and their profession. They exercise critical thinking skills and develop self-guided learning strategies. Simulation offers an opportunity to both broaden and deepen coverage while enhancing student learning.

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# AUTHOR GUIDELINES

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

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

## • Specific suggestions on preparing papers •

**TITLE** • Use specific and informative titles. They should be as brief as possible, consistent with the need for defining the subject area covered by the paper.

**AUTHORSHIP** • Be consistent in authorship designation. Use first name, second initial, and surname. Give complete mailing address of place where work was conducted. If current address is different, include it in a footnote on title page.

**TEXT** • We request that manuscripts not exceed twelve double-spaced typewritten pages in length. Longer manuscripts may be returned to the author(s) for revision/shortening before being reviewed. Assume your reader is not a novice in the field. Include only as much history as is needed to provide background for the particular material covered in your paper. Sectionalize the article and insert brief appropriate headings.

**TABLES** • Avoid tables and graphs which involve duplication or superfluous data. If you can use a graph, do not include a table. If the reader needs the table, omit the graph. Substitute a few typical results for lengthy tables when practical. Avoid computer printouts.

**NOMENCLATURE** • Follow nomenclature style of Chemical Abstracts; avoid trivial names. If trade names are used, define at point of first use. Trade names should carry an initial capital only, with no accompanying footnote. Use consistent units of measurement and give dimensions for all terms. Write all equations and formulas clearly, and number important equations consecutively.

**ACKNOWLEDGMENT** • Include in acknowledgment only such credits as are essential.

**LITERATURE CITED** • References should be numbered and listed on a separate sheet in the order occurring in the text.

**COPY REQUIREMENTS** • Send two legible copies of the typed (double-spaced) manuscript on standard letter-size paper. Submit original drawings (or clear prints) of graphs and diagrams on separate sheets of paper, and include clear glossy prints of any photographs that will be used. Choose graph papers with blue cross-sectional lines; other colors interfere with good reproduction. Label ordinates and abscissas of graphs along the axes and outside the graph proper. Figure captions and legends will be set in type and need not be lettered on the drawings. Number all illustrations consecutively. Supply all captions and legends typed on a separate page. State in cover letter if drawings or photographs are to be returned. Authors should also include brief biographical sketches and recent photographs with the manuscript.

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Milliken is a major manufacturer of textile products for apparel, commercial, home, and industrial markets, as well as specialty chemicals for a wide variety of applications. The company was founded in 1865 and has nearly 50 plants and 13,000 associates in the US. Milliken is a world leader in quality manufacturing and was the 1989 winner of the Malcolm Baldridge National Quality Award. Careers at Milliken involve challenge, innovation, advanced technology, promotion from within based on individual performance, and extensive education and training opportunities. Entry level opportunities are available in South Carolina and Georgia.

***CITIZENSHIP REQUIREMENTS:*** U.S. citizenship or Permanent Resident Visa

***REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED:*** Southeastern United States

***HOW TO APPLY IF UNABLE TO SCHEDULE A CAMPUS INTERVIEW:*** Send cover letter with functional area interests and geographic preference statement, resume, and a copy of your transcript to the above address.

### BS / MS

*Process Engineering:* ***Provides technical support in textile dyeing and finishing operations and in Specialty Chemicals production. Responsibilities include manufacturing compliance with customer product quality specifications and process efficiency/improvement project assignments.***

*Manufacturing Management:* ***Responsible for the production resources of people and machinery. The first line production manager may be promoted to either Advanced Production Manager or Process Engineer in the dual career ladder.***

*Research:* ***Develops new products and associated machinery or processes. Prefer PhD, but will consider MS***

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