DENDY SLOAN
of the Colorado School of Mines

CHE AT UTAH

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SWITZERLAND, SPAIN: Information Science ......................... KUT, QUERALT, ROSE
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Dendy Sloan
of the
Colorado School of Mines

BRODIE FARQUHAR
Colorado School of Mines
Golden, CO 80401

“DENDY SLOAN IS AN academic man for all seasons,” said Art Kidnay, department head of Chemical Engineering and Petroleum Refining at the Colorado School of Mines. “He is one of those rare individuals who does everything well.”

Professor Sloan is a renaissance figure, on a campus and in a discipline dominated by specialists. “Dendy is the most balanced, well-rounded faculty member I know,” said Kidnay. “That is what sets him apart. Other faculty on campus and around the nation are equally competent in areas like teaching, committee assignments, research, engineering education research, and work in the professional societies—but I don’t know anyone quite as good in all areas.”

The shelves in Sloan’s office contain the usual and the unexpected. Chemical engineering texts and journals dominate, as do two large models of hydrate molecules. What is different is the strong presence of books of philosophy and literature. Books like *Zen and the Art of Motorcycle Maintenance* by Robert Persig, and Whitehead’s *The Aims of Education* nestle with books by William Shakespeare, Herman Hesse and Robert Frost. The hydrate molecular models represent the specialization Sloan has sought, while the philosophy and literature books represent a curiosity that has never been satisfied with the comfort of settling into a familiar niche.

“Dendy teaches a variety of courses,” said Kidnay, “and by next year, he will have taught every undergraduate course in our department. He’s done this voluntarily. Very few faculty can or would do something like that—most prefer to specialize near their own research interests, which makes it easier to teach. I know that some schools have a policy to force faculty to rotate through the curriculum in the interest of balance and keeping up with all areas of your discipline. We don’t have that policy, simply because most of us don’t have the time. Dendy is the only one I know who could pull it off.”

Born in Seneca, South Carolina, in 1944, Dendy developed an early interest in math, science, chemistry, and physics in high school. He earned his BS in chemical engineering from Clemson University in 1965 and worked five years for duPont, working in Tennessee, Delaware, West Virginia, and South Carolina. “In the course of those four jobs with duPont,” said Sloan, “I discovered that I enjoyed opportunities to be entirely self-motivated and directed. Teaching seemed like a good way to do that.”
In light of his later professional accomplishments, getting into graduate school should not have been a problem. It was. “Dendy did not have outstanding grades as an undergraduate,” said his Clemson uppergraduate advisor, Dr. Joseph Mullins. “As I recall, he was active in a band and still plays a pretty hot banjo. The department chairman suggested he take some math courses and reapply.” Several night courses and A’s later, Sloan entered the graduate program at Clemson.

“Dendy was the most organized student I’ve ever had,” said Mullins. “He came early and stayed late and ran during the lunch hour. Pretty soon he had most of the grad students chugging away, running with him.” (Sloan has run 12 marathons and typically has put in 40 miles per week over the past 20 years.)

It was at Clemson University that Sloan’s role models for teaching made their impact on his career. “Clemson had an unusually strong focus on education,” said Sloan. “People like Joe Mullins, Dick Harshman, and department chairman Charles Littlejohn had a real impact. As I got into graduate education, I realized that this was what I wanted to do with my life.”

Sloan earned his MS from Clemson in 1972, with the thesis title of “The Combined Effects of Natural and Forced Convection in a Dual Membrane, Horizontal Parallel Plate Ultrafilter”; and his PhD in 1974, with the thesis title of “Nonideality of Binary Adsorbed Mixtures of Benzene and Freon-11 on Highly Graphitized Carbon at 298.15 K and Pressures below 10 Torr.”

“I advised Dendy to get his PhD elsewhere,” said Mullins, “but he insisted on getting it here. I did persuade him on the wisdom of doing postdoctoral work elsewhere.” Elsewhere turned out to be Rice University, where Sloan encountered Dr. Riki Kobayashi and worked as a research fellow on determining the water content of a high pressure natural gas pipeline, from Alaska to the lower 48. Sloan has run 12 marathons and typically has put in 40 miles per week over the past 20 years.)

It was a very high pressure time and environment,” said Kobayashi. “Dendy was responsible for measuring and setting the water content specs for a high pressure natural gas pipeline, from Alaska to the lower 48. Dendy, along with Jerry Holder (currently at the University of Pittsburgh), is currently recognized as one of the primary researchers (in addition to Dr. Kobayashi) in the area of hydrates. The energy crisis really had us going—so much so that I bought a rollaway bed for Dendy. He never complained.”

Methane hydrates are a molecular bond of water and natural gas, under pressure. Under certain conditions, hydrates can build up in a pipeline and plug it.

From that initial focus on hydrates as a problem, Sloan eventually branched out to explore methane hydrates as an energy solution. Rich fields of methane hydrates exist in deep oceans, as well as in permafrost regions of Canada, Alaska and Siberia. It is estimated that under United States land and territorial waters alone, there are enough hydrate deposits to provide natural gas supplies for at least 150 years, or 15 times the known supply of conventional natural gas. This unconventional form of natural gas is currently thought of as a future resource, and some of Sloan’s research studies is currently sponsored by the U.S. Department of Energy.

Sloan came to the Colorado School of Mines in 1976. Here he taught most of the undergraduate courses, specializing in thermodynamics, phase equilibria, and stagewise process design at the graduate level. His research proceeded with natural gas hydrates and included adsorption, phase equilibria, and thermal conductivity. He came for the professional opportunities, the high caliber of students, and the high degree of latitude Mines offers its faculty, who enjoy both teaching and research. He has stayed for these and other reasons.

“This is small town America,” said Sloan, referring to his nine years in Golden. “You have the friendliness of a small community—Cub Scouts, a good church—and access to a big city. This is a good family place.” That’s important to Sloan and his wife, Marjorie, and his two sons—Tre, 13 and Mark, 10. Sloan has been active in the Scouting movement for six years and has served as an elder in the Presbyterian Church. Marjorie is a second year law student at the University of Colorado. “I’ve had offers for other positions, yet I haven’t been able to convince myself that I’d be happier elsewhere,” said Sloan.

Has he noticed any similarities between Cub Scouts and college students? “Eight- to ten-year-olds are bundles of unchanneled energy. You’ve
got to plan things that will hold their interest; otherwise they climb the walls. Students 18-22 years old are generally very bright and very channeled,” said Sloan. “Graduate student personalities typically mirror those of the professor, but undergraduates can be a substantially different challenge. Working with undergraduates is one of the best motivators for coming into this profession, and when a school has as good students as CSM does, it makes teaching doubly pleasurable.”

Evidently, his ability to hold an eight-year-old’s attention has rubbed off on his college teaching style. Students consistently rank him as one of the best teachers on campus, year after year. His peers have also recognized his teaching skills by honoring him with the AMOCO Teaching Excellence Award at CSM, and with the Western Electric Award from ASEE.

Currently, Sloan works with eleven graduate students in research focused on natural gas hydrates, vapor liquid equilibrium, and thermal conductivity. In 1982, Dr. Sloan acquired the first Western sample of methane hydrates when the Glomar Challenger brought up samples from the ocean floor off the coast of Guatemala. Shipped in chilled and pressurized containers to Sloan, the “dirty snowballs” have been divided up among laboratories at CSM and other schools. Sloan and his graduate students are trying to determine optimum in situ methods of releasing condensed methane molecules from the water molecules which surround them.

One of the frustrations of running a successful research operation is lack of time for personal, hands-on research. “We come in as researchers and become research managers. There is no time for lab work. I find time for some theoretical and computer work, but I really miss working in the lab,” said Sloan.

In spite of these limitations, Sloan does find time for a number of other activities. These include professional service in the ASEE and other organizations, service on a variety of CSM committees, work with the innovative EPICS program at Mines, plus pondering philosophies of engineering education. He even finds time to study the personalities of faculty and students, correlating results with their career tracks.

Within the ASEE itself, Sloan is currently Chairman of the Educational Research and Methods Division and is Chairman-Elect for the Chemical Engineering Division. Within CSM, Sloan has served as chairman of the Honors Humanities Tutorial Committee, and served on the Presidential Search Committee.

“EPICS” stands for Engineering Practices Introductory Course Sequence. Because the best method for mastery of any skill is regular practice, EPICS has been designed by Sloan and other CSM faculty as a unique lab-type course, providing “real-world” environments to develop and practice engineering skills. “The emphasis is on the process of learning, not the content of engineering facts and figures. All the facts, figures and cookbook procedures we pound into students’ heads have a half-life, a limited time-span of value, due to the explosion of information and research. Once a student learns the process of learning and solving real-world, open-ended problems, he or she will never have to worry about the half-life of his or her knowledge—they’ll be life-long learners,” said Sloan.

“We’re still teaching like Saint Thomas Aquinas in the Thirteenth Century, lecturing in front of a group of students. How do we integrate new tools like computers? They are no panacea, yet I believe that the key is in experiential learning, case studies, and real-life problem solving. Mines and Harvey Mudd are two of the best places I know that are working toward this new approach of engineering education,” said Sloan.

The shift from content to process will not come easily, warned Sloan. “High school teachers put a great deal of emphasis on content (students regurgitating books and lectures), as do colleges, yet we expect colleges to produce leaders and in-
and to integrate intuitive and sensing methods of comprehension, and run out of time.

It also forces educators to look closely at how students feel about the process of learning. "I'm convinced that if a student leaves a course or a school feeling badly, then we've done permanent damage to that student. He/she won't be as good an engineer as someone who left a course or school excited about what they learned. As a profession, we're not doing a good job of addressing this issue."

Sloan enjoys reading philosophy and does not see the discrepancy between the "real world" and the "world of ideas." For Sloan, engineering and philosophy are both concerned with open-ended problems. "I try to see things as part of a spectrum, not as different or isolated from the whole. Take Robert Persig's Zen and the Art of Motorcycle Maintenance. It presents the classic struggle between objective science and intuitive romance and shows that rather than being estranged from each other, they can be part of a whole," said Sloan.

Personality types fit into this world view. Using the Myers-Briggs Type Indicator (MBTI), Sloan has found that different personalities have different world views and are attracted to different disciplines (see "Applications of Psychological Types in Engineering Education", February 1983, Engineering Education).

Some people are attuned to the practical, hands-on, common-sense view of events, while others are more attuned to the complex interactions, theoretical implications or new possibilities of events. These two styles of information gathering, or perception, are known as Sensing and Intuition, respectively.

"Since faculty are predominantly intuitive," said Sloan, "and students are evenly split, I'm concerned that we may be awarding grades based on personality characteristics, rather than performance." Intuitives do better on exams prepared by intuitive type faculty, while sensing types do less well—usually because they re-read every test problem in the interest of accurate comprehension, and run out of time.

For Sloan, balance or integration is a key concept. Just as a mature personality should be able to integrate intuitive and sensing methods of learning, a mature profession (engineering education) should be able to integrate content and

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PROJECT ENGINEERS, Specialty Chemical Manufacturing Company in Southwest Pennsylvania seeks candidates to direct all process development activities for Emulsion Polymer project. Requirements: Resume, PhD Chemical Engineering plus 2 years experience as Project Engineer or Chemical Research Engineer, PhD and employment experience must be in polymer rheology and engineering. $47,088/year. Full time. Send resume to Charles A. Wilson, Office of Employment Security, 300 Liberty Avenue, Room 1302, Pittsburgh, PA 15222. Job Order #3990818 DOT #019.167-014.

process methods of teaching. To all who know him, Dendy Sloan exemplifies a sense of balance and wholeness, as an individual and as a professional educator. □
CHE AT THE UNIVERSITY OF UTAH

NORMAN W. RYAN
University of Utah
Salt Lake City, UT 84112

The University of Utah, located in Salt Lake City, occupies 1,500 acres and is bounded on the east by the Wasatch Mountains. Founded in 1850, it is the oldest and, with a student population of about 25,000, the largest institution in Utah's system of higher education. Its essential functions are served by a faculty of about 3,500, with roughly half being regular teaching faculty and half being adjunct, research, clinical, and visiting faculty. The governance of the university includes a Board of Regents and an Institutional Council (both appointed by the governor) to whom the university president reports.

The university is a complete university in the sense that it contains a good library and a set of professional colleges (including a renowned medical school) with supporting general education and scholarly departments, housed mostly in the colleges of science, humanities, and fine arts. This proximity allows interesting collaboration among the diverse professionals and scholars. The College of Engineering is one of the eleven academic colleges and consists of seven departments, one being the Department of Chemical Engineering.

All seven departments of the college are presently housed in the Merrill Engineering Building except for what has spilled over as the college has outgrown its building space. Research has expanded to fill the newly completed Energy and Minerals Research Laboratory Building, and a new classroom building (to be shared with another...
other college) will be available in about a year. The spillover will be reabsorbed, and current needs met.

There are rumors about hazards said to exist in associating with the University of Utah; namely, the seductiveness of the easily accessible outdoor life in mountains, canyonlands, and deserts. Other enticements to postpone one's urgent duties are afforded by the performances of a symphony orchestra, a ballet company, an opera company, a modern dance company, and several small theatre groups. All are resident in Salt Lake City, and most trace their genesis to the university campus. The locals tend to euphemize the risk of these “hazards” by praising the character-building effects of resisting temptation—but we tolerate (as we practice) yielding with moderation.

**HISTORY**

For the present purpose, history is either ancient (1905-1947) or modern (1947-present). In 1905, a program in chemical engineering was first listed among the offerings of the State School of Mines. The first B.S. in chemical engineering was awarded in 1907. By the middle 30's the Chemistry Department was administering the program, but the curriculum was still listed by the School of Mines and Engineering.

In 1943 George W. Minard, the first chemical engineer to be recruited, joined the chemistry faculty to supervise the chemical engineering program. Because Selective Service shanghaied his clientele, he took leave to serve in a local war industry, returning full time to graduate the class of 1947, and then resigning.

Modern history begins in 1947 with the fission of the College of Engineering and Mines into the College of Engineering and the College of Mines and Mineral Industries. E. B. Christiansen was retained as head of the new department of chemical engineering and was given the choice of affiliating with either of the two colleges. He chose engineering and, despite the fact that some of the top administrators withheld their blessings, hindsight has confirmed the wisdom of the choice.

Professor Christiansen, with some initial outside help in teaching, first concentrated on recruiting faculty and building a projects laboratory. Parts of the apparatus were assembled from war surplus equipment and parts were designed and, to a large extent, built by undergraduate chemical engineering students. After two years the labora-

tory was creditable, two new faculty members had joined the faculty, and 37 new BS degrees and the first MS degree had been awarded. The department was ready to apply for accreditation, applied, and was accredited in 1952.

During “Modern” times, the regular faculty has grown on the average of one every three years. Of the 15 members signed aboard, only two have left, one by resignation and the other by involuntary transcendental reassignment. Probably, unless the academic charter of the department is altered, the faculty will not be increased much more; future recruits will be replacing those who depart.

**FACULTY**

There are thirteen live bodies on the active faculty, eleven regular, one senior research professor, and one emeritus still active in research. Since part of the efforts of several are devoted to nondepartmental duties, we report only about nine full-time-equivalent faculty. The thirteen members of the faculty (14 including a newly hired Assistant Professor) have earned their doctorates at ten respected universities. All have experience in industry and over half have taught elsewhere at the university level.

With respect to professional recognition at the national level, one of the faculty, a member of the National Academy of Engineering, is a past president of both the American Institute of Chemical Engineers and the American Institute of Mining and Metallurgical Engineers, two have been awarded the AIChE Founders’ Medal, three have been directors of the AIChE, three are Fellows of the Institute, and one was the annual Institute Lecturer for the Institute’s Diamond Jubilee year. One has received the NSF “Young Presidential Investigators” award.
Two kinds of prized recognition within the university are the awards for outstanding teaching, five to ChE faculty members, and outstanding research, three to ChE faculty members.

All but the newest recruits have served in the less prestigious but important offices and committees, national or regional, of the Institute, other professional societies, and governmental agencies. As is appropriate in a university where the principle of faculty governance of academic matters is nominally respected (though sometimes needing defense), all faculty serve, or have served, on policy, executive, and administrators’ advisory committees.

The present faculty members are: Richard C. Aiken (Associate Professor), PhD, 1973, Princeton University; Alva D. Baer (Professor), PhD, 1959, University of Utah; Richard H. Boyd (Professor), PhD, 1955, MIT; E. B. Christiansen (Professor), PhD, 1945, University of Michigan; Donald A. Dahlstrom (Research Professor), PhD, 1949, Northwestern University; Noel de Nevers (Professor), PhD, 1959, University of Michigan; George R. Hill III (Eimco Professor), PhD, 1946, Cornell; Timothy Oolman (Assistant Professor, beginning Autumn, 1985), PhD, 1985 University of California, (Berkeley); David W. Pershing (Professor), PhD, 1976, University of Arizona; Norman W. Ryan (Professor Emeritus), ScD, 1949, MIT; Dale L. Salt (Professor), PhD, 1959, University of Delaware; J. D. Seader (Professor), PhD, 1952, University of Wisconsin; Edward M. Trujillo (Associate Professor), PhD, 1975, University of Utah; and A. Lamont Tyler (Professor and Chairman), PhD, 1965, University of Utah.

STUDENTS

Aside from striving together for an education focused on chemical engineering, our undergraduate students rely little on the campus to cultivate their social life. Most live off-campus, many have part-time employment in the city, and a significant fraction are married. Yet through their shared experiences in classes and in the undergraduate seminar, managed by the student AIChE chapter officers, they develop an impressive esprit de corps.

The spirit has manifested itself in the last seven years in the regional AIChE student paper competition: first place five times, second place five times, third place four times. The national Student Chapter Award of Excellence has come to Utah in seven of the last eight years. The chapter's advisor, A. L. Tyler, received one of the National Outstanding Student Chapter Counselor Awards in 1978 and again in 1983.

Other interesting sightings of the spirit are made during the annual undergraduate student vs faculty (plus drafted graduate students) basketball game, the junior vs senior softball game, the annual student vs faculty doubles tennis match (in which the faculty remains undefeated), and the spring luncheon at which the seniors are guests of the faculty. On this last occasion the faculty experiences (and sometimes provokes), the students' traditional irreverence, which passes from calmly suppressed to delicately expressed.

With respect to statistical demography, we regularly graduate 35 to 40 students with the baccalaureate each year. The numbers of advanced degrees awarded during the last ten years were 81 Master of Engineering, 27 Master of Science, and 30 Doctor of Philosophy. Our present facilities and faculty enable us to handle a greater flow of graduate students.

UNDERGRADUATE PROGRAM

That the curricula of all the chemical engineering programs in the country are very similar follows from the wide consensus among faculties on the essential ingredients of the overall program. Outside that core of consensus we find differences in emphasis, depth, or diversity.

In Utah's chemical engineering, the most notable instance of emphasis is seen in the three-quarter senior projects laboratory. Two or three students, as a team captained alternately by the members, are assigned eight laboratory projects during the senior year. An assignment is typically a design problem which requires that the team operate laboratory equipment to generate the design data needed. With assignment in hand, the team identifies appropriate equipment (or some-
times must assemble it), learns how to use it, and determines what data to take. Next they schedule a group oral examination by a faculty supervisor, and when they persuade him that they understand the project, they proceed to the final frustrations: producing the data, using the data, and writing the report.

In the course of the year's projects, the student writes three detailed formal reports, and his other five reports are technical notes or letter reports. Every report is first read by a non-engineer who grades it for the mechanics of composition and sometimes rejects it with suggestions for improvement. When it finally passes the preliminary reading, it goes to the faculty supervisor who will judge its form and engineering content. A late report is downgraded significantly. On the other hand, a report reflecting unusual ingenuity in experiment or design is awarded a grade bonus.

Another emphasis, perhaps its distinctiveness already swept away by time's frantic broom, has been our use of computers in homework and laboratory instruction. In the laboratory, many experiments are monitored or controlled by microcomputers or minicomputers. In most departmental courses, computer time is made available for the students on the computer center's mainframe computer, and techniques requiring its use have become an integral part of the coursework. Of particular note has been leadership, through J. D. Seader, in instruction in the use of large process simulation programs such as ASPEN, FLOWTRAN, and CHEMSHARE. During the final quarter, each student is required to complete a technical and economic design optimization using one of these tools.

We do not treat the diffusional processes collectively as transport phenomena or under other non-descriptive titles. Rather we share with mechanical and civil engineering departments the teaching of common courses in engineering thermodynamics, fluid mechanics, and heat transfer. The students' class scheduling problems are greatly reduced. The required mass transfer courses are taught only in chemical engineering.

Many students desire some specialization, and we try to guide them in choosing the appropriate elective courses. To that end, we have established several informal options such as living systems, digital control, and management; or we may approve alternative schemes of electives proposed by them.

**GRADUATE PROGRAM**

Four advanced degrees are offered in the department: Master of Engineering (ME), Master of Science (MS), Master of Philosophy (MPhil), and Doctor of Philosophy (PhD). Each aspirant is limited with respect to which of the degrees he may apply for, depending on his performance in a combination diagnostic and screening examination. This preliminary judgment may be appealed later on the basis of the student's subsequent performance.

The ME degree, design-oriented, is popular with BS-ChE holders and graduates from related fields who want advanced treatment of chemical engineering, with opportunity for further study in related fields or mathematics. Much the same can be said for the MS degree, except that it is research-oriented and it is sometimes a first step to the PhD.

The PhD is a research degree for which candidacy is deferred until the aspirant passes a qualifying examination. That examination takes the form of preparing and defending a research proposal in which the prospective candidate is required to demonstrate originality and independent thought. The dissertation, with very rare exceptions, must exhibit an essential experimental component.

**RESEARCH**

Research in Utah's chemical engineering department is aimed at the education of degree candidates, with the faculty's role being maximally advisory, minimally supervisory. The benefits of the research in faculty development are regard-
ed as a bonus. Most (if not all) single-author publications by the faculty have not been designed to present new research findings, but rather have been intended to be either pedagogical, critical, or entertaining.

A furnace used in research on air pollutant formation.

The line of research of greatest longevity in the department has dealt with the rheology of non-Newtonian fluids, both the characterization of detailed fluid motion and its use in describing bulk flow. Related but independent projects have dealt with two-phase flow, with liquids and solids distributed in gases, with solids and gases distributed in liquids, and with fluid mechanics and heat transfer for flow in curved tubes with and without chemical reaction. In addition, a study of the fluctuating boundary layer in nominally “steady-state flow” was made.

The research having the longest period of continuous sponsorship, and consequently generating the largest number of advanced degrees, has studied the combustion of condensed fuels. The chief interest has been in the transients of ignition, oscillating combustion, and extinguishment. Much of the effort has involved the burning of solid composite rocket fuels, and some, the burning of the polymers and oxidants separately, with clear relevance to fires. This work qualified the University of Utah to host the Thirteenth Symposium (International) on Combustion on our campus in 1970.

The combustion research activity just mentioned has diminished in intensity. Meanwhile, another class of combustion projects has become the most active. This research involves coupled experimental and theoretical work on the control of acid rain pollutants (primarily NO, NO₂, SO₂, and SO₃) under conditions typical of those found in coal-fired industrial furnaces, boilers, and kilns; the direct combustion of biomass fuels; and the incineration of hazardous industrial wastes in rotary kilns.

As one would expect in a university so situated, there is active research, though with a lesser sense of urgency than expressed a few years ago, on coals, oil shales, and tar sands. They are characterized and variously processed to produce liquid fuels.

A recent subject of research which has been advanced notably in this department is computer-aided process synthesis and design. Methods have been developed for synthesizing multicomponent separation systems based on considerations of second-law analysis. Most recently, robust computational procedures based on homotopy continuation have successfully been applied to interlinked separation systems, with the surprising discovery of multiple solutions.

**POSTSCRIPT**

If the reader has residual questions about chemical engineering at the University of Utah, he is invited to correspond with the chairman of the department, Professor A. Lamont Tyler.

**ChE book reviews**

**APPLIED COST ENGINEERING, 2nd Edition**
*by F. D. Clark and A. B. Lorenzioni*
*Marcel Dekker, Inc., 368 pages, $32.50 (1985)*

Reviewed by
*James H. Black*
*University of Alabama*

This book is a revised, updated, and expanded version of a very successful (six printings) predecessor. It is of particular use in explaining how to develop and use cost estimating tools, how to manage and use estimating data, how to avoid estimating pitfalls, and how to solve estimating problems. It also covers such topics as the use of estimates for cost control functions during the conceptual engineering, the detailed engineering, and the construction stages of project development. With the techniques described in this book, one can find out how to measure and forecast productivity and to control, rather than just report, costs. The book emphasizes cost estimating and Continued, next page.
CHEMICAL ENGINEERING DIVISION ACTIVITIES

TWENTY-THIRD ANNUAL LECTURESHIP AWARD TO DAN LUSS

The 1985 ASEE Chemical Engineering Division Lecturer was Dan Luss of the University of Houston. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. The 3M Company provides the financial support for this annual lecture award.

Bestowed annually upon a distinguished engineering educator who delivers the Annual Lecture of the Chemical Engineering Division, the award consists of $1,000 and an engraved certificate. These were presented to this year’s Lecturer at the Annual Chemical Engineering Division Banquet, held at the Georgia Institute of Technology.

ChE’s RECEIVE HONORS

A number of chemical engineering professors have been recognized for their outstanding achievements. Max Peters was the recipient of the Fred Merryfield Design Award, given annually to an engineering educator who exhibits excellence in teaching engineering design, and the Senior Research Award was presented to Robert Brodkey in recognition of his significant contributions to engineering research. Friedrich G. Heffrich, Richard D. Noble, and Richard M. Felder all received AT&T Foundation Awards, honoring cost control, two of the more important aspects of the field of cost engineering.

This book would find application as an advanced undergraduate-graduate level text in such courses as Process Design and Economics, Cost Engineering, Cost Estimating, Project Management, Project Control, and Construction Management. The first edition has found application this way since its appearance seven years ago, and this revised edition will continue that tradition. Practicing engineers, entering cost estimating for the first time, would find this book an indispensable aid.

For convenience, the book has been divided into three parts; namely, cost estimating, cost control, and case studies. Part III, the case studies, is a collection of ten examples to illustrate the principles of cost engineering. These case studies are designed to provide understanding of the underlying principles discussed in the first two parts of the book.

The new features of this book include, in addition to the case studies and the latest developments and improvements in cost estimating and cost control, several new aspects of cost engineering so that the book reflects recent advancements in the field. A new chapter on control of subcontracts has been added because of the increased importance of this topic today. There are Continued on page 161.
EDITOR'S NOTE: A controversy is brewing on the design content of the curriculum. The questions are 1) how much design should be required, and 2) how does one define “design”? In order to air these important questions, CEE is publishing the following two papers. Additional comments are solicited from our readers.

**ChE views and opinions**

**ARE WE PARTICIPANTS OR VICTIMS?**

JAMES WEI  
Massachusetts Institute of Technology  
Cambridge, MA 02139

This conversation, or something like it, took place at the San Francisco AIChE meeting among a group of distinguished professors and department chairmen of research universities.

“They are making a mess at accreditation (or choose one from: AIChE, NSF, ACS, ASEE, NAE, etc.). They are just a bunch of bean counters who do not understand that we should have innovations and diversity. And besides, who are they to tell us that our program is below standards? Have they ever managed a first-rate department themselves?”

“Why don’t you do something about it, suggest changes, organize a group, get involved?”

“I am much too busy with my students and papers. Somebody else should do it.” (i.e., somebody else not as good as we are, say a politician who cannot hack it in research and teaching.)

“But these are our own organizations that we depend on. If we won’t fix them, who else would do it?”

“We can send them an ultimatum, that if they do not shape up, we will quit.”

“We need to send them a detailed blueprint on how to reform their rotten organization. And if they cannot do it, we will have to start a new organization to administer accreditation, to set up new rules, to train new visitors, and to evaluate results. That would be even more work than reform from within.”

“Of course not, that would take too much time and effort.”

“You are mad enough to complain, but not enough to do something constructive—like volunteer for service. Shouldn’t we take the time to fix up our own organizations? No one else would have the knowledge or motivation to fix them to our specifications.”

“But that would be politics.”

“For instance, the AIChE Council of 17 contains only two professors. The accreditation committee and the ad hoc visitor list have very few professors from research universities. We believe in a trial by a jury of peers, and our peers are other research universities. If we will not sit on juries, we cannot be tried by a jury of peers—who understand us and are sympathetic to us. We should run for AIChE Council, or volunteer for ad hoc visitor in accreditation.”

“I am much too busy, and I am not interested in politics.”

“But politics affects us, and it has us riled up. If we are above politics, would we rather be victims or participants?”

“Let us go to the Exxon suite to drown our sorrows.”

The moral of the story is that it is better to be mugged than to participate in government, or isn’t it?

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THE TEACHING OF PROCESS DESIGN

EDITOR'S NOTE: The following paper, authored by the late T. K. Sherwood in 1959 while he was a faculty member at M.I.T., was sent to CEE by W. H. (Bill) Manogue, a member of the AIChE Education and Accreditation Committee. He credits E. L. Mongan, Principal Division Consultant in Du Pont's Engineering Service Division, for bringing it to his attention.

Professor Emeritus J. Edward Vivian of M.I.T. has written Dr. Manogue that he and Professor Wei (Head, Department of Chemical Engineering at M.I.T.) have reviewed the manuscript and "while he agreed with me that Sherwood's conclusion is not current, he felt that as long as the publication appeared with an Editor's note that this was a historical paper written in 1959, he had no objection to publication of the complete original manuscript."

We are pleased to be able to share this historical document with our readers, with the comments above.

T. K. SHERWOOD (Deceased)
Former professor at
Massachusetts Institute of Technology
Cambridge, MA 02139

It is suggested that engineering design can be taught effectively by introducing design problems into various theoretical subjects. A sample thermo problem is presented in detail as the best means of explaining just how this approach can be used in a course such as engineering thermodynamics.

If this technique is to be more generally employed at M.I.T., it is necessary that a large fraction of the engineering faculty be as interested and competent in the design aspects of engineering as they are in the scientific or analytical. The fraction so inclined is perhaps already too small and appears to be decreasing.

INTRODUCTION

The typical engineering accomplishment of importance results from a sequence of (a) recognition of a social need or economic opportunity, (b) a conception of a plan as to how the need may be met or the opportunity seized, (c) an analysis of the merits of the conception and of the consequences of proceeding with the plan, (d) the building or construction of the machine, plant or bridge as conceived, and (e) its operation. Item (c) is a sort of go no-go step; if the analysis is discouraging, the conception step and the analysis are repeated.

"Engineering science" is a phrase which has come into use in recent years to describe the analysis step. Good engineers today must be exceedingly proficient in analyzing a concept; quantitative mathematical analysis based on first principles is one of the good engineer's most powerful tools. But it no more constitutes engineering than any one of the other four activities listed. In particular, it must be noted that conception ("design") comes before analysis; the analyst must have something to analyze.

As technology develops, it seems likely that those engineers who can recognize social needs or economic opportunities and who can conceive and plan will be the men most sought after. They will be the ones who will hire the analysts (engineering scientists), the constructors, and the operators. To a large degree this is true today.

THESIS

The concept ("design") abilities of the student may be developed in at least three ways: (a) through design courses, planned to meet the need directly through lectures and exercises (this is the method used in architecture), (b) by subjects in which design problems are interwoven with the teaching of basic theory, and (c) by sticking to basic theory and the techniques of analysis, letting the student develop his own skill at inventive and conceptual thinking by exposure.
The teaching method I have in mind is best understood by studying an actual problem assignment. The example chosen is from engineering thermodynamics.

to the ideas and accomplishments of the great creative scientists.

The teaching of design by method (a) has not been well developed, except in connection with machines, aircraft, and architecture. Method (c) offers little promise for engineering. My thesis is that the second method can and should be more widely used in engineering education.

EXPLANATION

The teaching method I have in mind is best understood by studying an actual problem assignment. The example chosen is from engineering thermodynamics, partly because I teach this subject, but also because thermodynamics is one of the best examples of a subject that is often taught with no element of engineering design. It is a theoretical subject involving many abstract ideas and is normally expected to require rigorous thinking and exact calculations.

ILLUSTRATIVE PROBLEM

The following is a typical problem assignment to juniors about the middle of the first term of a two-term course in chemical engineering thermodynamics.

* * * * * * * * * * * *

Problem 10

A gas well in New Mexico produces essentially pure CO₂ at 800 psia and 100°F. The pressure is reduced to 200 psia by flow through a partially closed ("cracked") valve and delivered by pipeline to a plant several miles away. The flow rate is steady at 10 million ft³/day (reported as ft³ at 60°F and 1.0 atm).

The Joule-Thomson expansion through the adiabatic valve causes the gas to cool. This cold gas is used to provide refrigeration for a natural gasoline plant located near the wellhead. The condenser to be cooled operates at 60°F, and the minimum temperature difference for heat exchange is 5°F (i.e., the warmed CO₂ leaves at 55°F).

a) What is the temperature of the CO₂ leaving the valve?

b) What is the attainable refrigeration load, expressed as BTU/hr? (Comment—note how the instructor has made this sound like a practical problem by the wording. This is pure camouflage—the solution is simple and straightforward. The student is not asked to think—only to know how to use the first law and the Mollier diagram for CO₂.)

Solution

From the book, the first law flow equation is found to be

\[ Q - W_n = \Delta h \]

As applied to an adiabatic valve Q and W_n are zero, so the enthalpy leaving the valve is the same as upstream. This is read from the Mollier diagram to be 146 Btu/lb CO₂. At 200 psia CO₂ has this enthalpy at 5°F, which is the answer to (a).

At 55°F and 200 psia the enthalpy is 158 Btu/lb, as read from the chart. In the condenser Δh is 158-146 or 12 Btu/lb CO₂. From the first law flow equation as applied to the condenser

\[ Q - 0 = \Delta h \]

so the refrigeration amounts to 12 Btu/lb CO₂ flowing.

The specific volume of CO₂ at 60°F and 1.0 atm is read from the chart as 9.2 ft³/lb, so the CO₂ flow rate is

\[ 10,000,000/9.2(24) = 45,300 \text{ lb/hr} \]

The refrigeration load is then

\[ 45,300(12) = 543,000 \text{ Btu/hr} \]

This is the answer to (b).

* * * * * * * * * * * *

USE OF THE PROBLEM TO TEACH DESIGN

Now consider the problem so reworded as to invite the student to look at the design aspects of the situation.

The CO₂ flow rate is specified to be the same as before. The pipe line pressure is 200 psia, as before. Cooling water is available which can be used to cool the CO₂ stream to 70°F. The condenser to be cooled now operates at 20°F; the cold gas can be warmed only to 15°F so as to maintain the minimum temperature difference of 5°F.

The student is now asked: how much refrigeration is attainable from the CO₂ stream? How would the necessary equipment be arranged (i.e.,
draw a flow sheet)?

The routine M.I.T. "A" or "B" student sees the statement regarding available cooling water, notes that the feed gas is the only thing capable of being cooled to 70°F, and so refigures the problem with gas entering the valve at 70°F and 800 psia.

Enthalpy values from Mollier chart: feed gas, 146; gas at 800 psia, 70°F, 126; gas at 200 psia, 15°F, 148. Refrigeration is then

$$45,300(148-126) = 1,000,000 \text{ Btu/hr}$$

and

$$45,300(146-126) = 906,000 \text{ Btu/hr}$$

are removed by the cooling water. The flow sheet is shown in Fig. 1.

![Figure 1](image1)

A second student, probably a "B" or "C" man, goes through this same calculation, but in doing so notices that the CO₂ leaving the valve is partly liquefied. This is evidently a good thing. If all the CO₂ could be liquefied, there would be a very large amount of refrigeration. But available cooling water limits cooling to 70°F. The chart shows that CO₂ could be liquefied at 70°F if the pressure were about 865 psia. The well pressure is only 800 psia. But it should not take much power to compress the feed gas to 865 psia; the pump might be expensive because of the high operating pressure, but would be physically small because the gas density is high and the volumetric displacement low.

The second student’s flow sheet is shown in Fig. 2. The compressor is assumed to operate adiabatically and reversibly, and the pressure change is assumed to be isentropic. The first law gives the flow work as $-dh$, which is read from the chart as approximately 2 Btu/lb. The theoretical power required is

$$45,300(2)/3412 = 26.7 \text{ kw} \quad \text{or} \quad 35.6 \text{ hp}$$

which does not seem like much.

The CO₂ now leaves the cooler completely liquefied at 70°F with an enthalpy of only 65 Btu/lb. $\Delta h$ is zero through the valve, so the refrigeration attainable in the condenser is

$$45,300(148-65) = 3,760,000 \text{ Btu/hr}$$

The student does not know much about the efficiency or cost of compressors, but he concludes that even if the actual power were twice the theoretical, the compressor installation would appear to be well worth while in view of the very large increase in refrigeration attainable.

A third student follows the same reasoning and makes the same calculations as the second, but is troubled by the fact that the chart gives extremely poor precision in reading the $\Delta h$ of 2 Btu/lb in the compressor. He has learned that if kinetic and potential energy terms are neglected, $\Delta h$ for reversible flow is given as

$$-\int vdp$$

Reading the chart, he finds the specific volume of the feed gas to be 0.115 ft³/lb and that of the gas compressed isentropically to 865 psia to be about 0.105. An average value of 0.11 ft³/lb cannot be more than 5% in error, so

$$\Delta h = 0.11(865 - 800)(144/778) = 1.32 \text{ Btu/lb}$$

from which he calculates the theoretical (adiabatic reversible) compressor power to be 17.5 kw.

A fourth student makes the same calculations as the second or third student, but hates to see the gas go to the pipeline at 15°F. Cannot this cold gas be useful? Water cooling to 70°F certainly was. Using the cold gas to partially cool the liquid CO₂ leaving the gas-water heat exchanger. His flow sheet is shown in Fig. 3.

Continued on page 164.
SOME EXPERIMENTS which the author ran in 1980-81 in the University of Edinburgh's third year chemical engineering laboratory are shown in Table 1. Fluid mechanics and thermodynamics laboratories are taken separately. This is the major chemical engineering formal lab, since the student does research and design projects in the fourth year of the course. The students work in pairs, starting at 10:00 a.m. and finishing nominally at 5:00 p.m. (in practice, between about 3:00 and 6:00 p.m.). The lab runs for two terms. In the third term of the session the weekly lab is omitted and there is a ‘lab week’ instead where the students devote the whole of one week to an open-ended short project, such as the development of a new lab experiment. This paper remarks on features of the experiments which might make them attractive for wider use.

CONVECTIVE MASS AND HEAT TRANSFER

Good convective mass transfer experiments are hard to find. This writer's experience with wetted wall columns, for instance, has not been happy. The purpose of this experiment is not the study of simultaneous heat and mass transfer, but the study separately of convective heat and mass transfer in the same geometry, to allow the j-factor analogy to be confirmed. The apparatus was originally a commercial heat transfer experiment, consisting of a 12.5 cm square duct with a perspex test section, through which air is drawn by a blower. Transverse rods of 1.25 cm diameter are introduced through holes in the wall, to simulate up to four rows of a heat exchanger tube bank: all the rods but one are perspex dummies. The working rod is copper and has a thermocouple within it. This rod is heated electrically and then inserted into place at the start of the experiment. From its cooling curve the gas-rod heat transfer coefficient is deduced, and the experiment is repeated for different air velocities and test-rod positions. Measured pressure drops are also logged. Next, the mass transfer runs are performed.

The adaption to mass transfer work exploits...
Bill Paterson lectured at Edinburgh after taking his BSc and PhD there. He has been a development manager with I.C.I. Petrochemicals Division and is now a University Lecturer in chemical engineering and Director of Studies in chemical engineering at Corpus Christi and Sidney Sussex Colleges, Cambridge. His research interests include chemical reaction engineering, packed bed operations, flowsheet simulation and process synthesis.

Macleod's swollen polymer method [1, 2]. A thin film of commercial silicone rubber is deposited on the surface of the mass transfer working rod. This is swollen to equilibrium with some suitable volatile agent, e.g., ethyl salicylate. When the rod is placed in the air stream the agent evaporates. There is a constant rate drying period during which the partial pressure of the swelling agent immediately above the polymer is sensibly constant, equal to its saturated vapour pressure at the air temperature, and the controlling mass transfer resistance is rod-gas convection; diffusion through the polymer does not intrude. Intermittent withdrawal and weighing of the rod both establishes the mass transfer rate (and thus the mass transfer coefficient, for the partial pressure of swelling agent in the bulk gas is virtually zero) and confirms that the test is within the constant rate period. The rod can then be immersed in a test-tube of swelling agent for re-swelling to equilibrium, while a different test rod, ready prepared, is used for the next run. Since saturated vapour pressure is sensitive to temperature, it is important to measure the air temperature with more accuracy (e.g., ± 0.1°C) than the heat transfer experiment requires.

The transfer coefficients are then nondimensionalised, to show that the restricted j factor analogy, \( j_0 = j_H \), holds, while the presence of form drag falsifies the complete j factor analogy \( j_0 = j_H = f/2 \), where f is the friction factor. Alternative swelling agents, appropriate values of saturated vapour pressure and diffusivity, and other simple experiments using the swollen polymer method are reported elsewhere [3, 4].

HEAT TRANSFER TO A JET

A flat horizontal sheet of plastic, of area A, incorporating a commercial liquid-crystal temperature-sensitive film, is heated from below by direct contact with an electric heating mat. The relation between sheet temperature and colour is established in preliminary experiments. The mat sits on insulating material so that all its power, W, measured as current times voltage, passes through the sheet. The sheet quickly reaches a thermal steady state, so that, in still air, it has a uniform colour. A round, laminar air jet is then aimed at the centre of the sheet, normal to its surface. Then, since the solid-air heat transfer coefficient, \( h \), varies with position, r, so does the surface temperature of the film, \( T_s \), and coloured rings appear on the film. The heat transfer coefficient, as a function of r, is calculated from

\[
h(r) = \frac{W}{A[T - T_s(r)]}
\]

and compared with theory [5]

\[
Nu(r) = 0.159 Pr^{1/3}Re^{3/4} (d/r)^{5/4}
\]

where d is the diameter of the jet.

The experiment is repeated with a square jet for which no theory exists, and the students explore the unexpected and interesting results. An improved and abbreviated (two hour) form of this experiment has been transplanted to the second-year fluid mechanics and transport processes lab in Cambridge. Details may be had by writing to Mr. N. MacFadyen.

DIFFUSION EXPERIMENTS

Usefully accurate gas diffusivity measurements can readily be made in a Stefan experiment [6] where evaporation rates are measured from a long-necked flask. However, this experiment does not involve the direct measurement of concentration profiles and is consequently found unsatisfactory by some students. The two experiments used in this lab are selected to remedy this defect, to show the difference between equimolecular counter-diffusion and diffusion through...
a stagnant film, and to introduce the student to some moderately heavy mathematics and to some analytical instruments.

The counter-diffusion experiment is Gover's [7]. About 5 ml of, e.g., acetone vapour is injected through a septum near the bottom of a vertical, lagged sealed glass tube (length ca. 60 cm, i.d. 2.5 cm) containing, as host gas, nitrogen traced with 3% ethane. A subsequent series of analyses of samples withdrawn (by 100 µl gas-tight syringes) at two sample points each located at one-sixth of a tube length from an end permits determination of $D_{AB}$, the diffusivity of the vapour in nitrogen. The acetone concentration in counter-diffusion is described by the diffusion equation (Fick's second law)

$$\frac{\partial C_A}{\partial t} = D_{AB} \frac{\partial^2 C_A}{\partial Z^2}$$

with $t = 0$, $C_A(Z) = C_A^0(Z)$

$Z = 0, L$, $\frac{\partial C_A}{\partial Z} = 0$

where $Z$ is the axial coordinate, $t$ is time, and $L$ is the tube length. The solution for $t > 0$ is obtained by separation of variables

$$C_A(Z,t) = A_0 + \sum_{k=1}^{\infty} A_k \exp \left( - \left( \frac{k\pi}{L} \right)^2 D_{AB} t \right) \cos \left( \frac{k\pi Z}{L} \right)$$

where the values of the coefficients $A_0 \ldots A_k$ depend on the initial concentration $C_A^0(Z)$, that is, on the particular $Z$-wise concentration profile set up on completion of injection ($t = 0$). Taking the difference of concentration between two points at the same time, the even terms cancel and the odd terms double. The location of the sample points causes the term in $A_1$ also to vanish, while the decaying exponential factor causes the terms in $A_k$ higher to be negligible for all but the shortest times. Hence

$$[C_A(1/6 L, t) - C_A(5/6 L, t)]$$

is proportional to

$$\exp[ - \frac{\pi^2}{L^2} D_{AB} t]$$

Thus the slope of a plot of the logarithm of that concentration difference against time yields $D_{AB}$. The unknown and unimportant $A_1$ is included in the intercept. Since a difference in vapour concentration is required, considerable error would result if the sample volumes were not identical. The purpose of the ethane tracer is to permit correction for differing sample volumes by use of the areas of the ethane peaks from the GLC. Note that calibration of the GLC is unnecessary so long as peak area is proportional to the moles of species in the sample, since acetone peak areas (corrected using ethane peak areas) may be used in place of molar concentrations in the difference term above: the intercept of the plot changes, but not its slope.

The stagnant film experiment is Crosby's [8]. Here the film is arranged to be very thick—it occupies a diffusion cell about 0.4 m high. A pile of discs with a hole in each is assembled on a central pivot and can be arranged so that the holes are in line to form a vertical tube. At the bottom a reservoir carries a volatile liquid, e.g., acetone. At the top a cap has a stream of nitrogen flowing through it. It is assumed that the concentration of vapour at the bottom is due to the vapour pressure at room temperature; at the top it is always zero. Starting with nitrogen only in the system, vapour is allowed access at zero time. At any subsequent time, $t$, vapour will have diffused towards the top. At time $t$, alternate discs are rotated to isolate each section of the cell. A stream of nitrogen is used to flush out each section in turn and a quantity proportional to the vapour mole fraction is determined by a thermal conductivity cell (katharometer) attached to a chart recorder. The shape of the vapour concentration profile is thus established.

The only important modification from Crosby's design is that 'O'-rings were recessed into the horizontal faces of the dural discs to seal them adequately. The mathematics is laid out in BSL [9]. In contrast to the 'long time' analysis above, the analysis here is for 'short' times so that there is no breakthrough of acetone into the top cell. Then a semi-infinite boundary condition is used ($Z = \infty, C_A = 0$), and solution is effected by Boltzmann's transformation or by Laplace transform. The text is careful to draw attention to the error which could occur by naive application of Fick's second law. The measured value of diffusion coefficient may be compared with that from the experiment above.

**ADIABATIC BATCH REACTOR**

An exothermic batch reaction is performed batchwise in a stirred Dewar flask, with progress followed by measurement of temperature, as described by Williams [10]. However, in addition to the reactions he recommends (sodium thiosulfate with hydrogen peroxide, and acetic anhy-
dride hydrolysis), there is provision for study of the acid-catalysed hydrolysis of propylene oxide to the glycol [11]. Assuming that this reaction is pseudo zero order in \( \text{H}_2\text{O} \), which is in great excess, and \( n^{\text{th}} \) order in propylene oxide, the heat and material balances yield the variation of temperature \( T \) with time \( t \)

\[
\frac{1}{(T_f - T)^n} \frac{dT}{dt} = \left( \frac{C_o}{T_f - T_0} \right)^{n-1} A \exp(-E/RT)
\]

where subscripts \( f \) and \( 0 \) imply final and initial. For an assumed value of \( n \), the values of the pre-exponential factor, \( A \), and the activation energy, \( E \), may now be estimated either by (a) numerical/graphical differentiation of the measured \( T \) vs \( t \) curve followed by plotting the logarithm of the L.H.S. versus \( 1/T \) [10] or (b) by a numerical integration method [11] in which experimental errors tend to be cancelled rather than amplified. Both of these methods are readily programmed for the microcomputer which logs the \( T \) vs \( t \) curve (receiving a thermocouple signal amplified and digitised by a DVM). Also programmed is an ordinary differential equation (o.d.e.) integration routine which permits integration of the o.d.e. above with the estimated values of \( A \) and \( E \) and the assumed value of \( n \). Thus the student can plot the predicted \( T \) vs \( t \) profile to compare with the experimental values, and choose the value of \( n \) (from, say, 0, \( \frac{1}{2} \), 1, 2) which gives the best fit. It is also possible then to predict profiles for different initial concentrations (\( C_o \)) or temperatures (\( T_o \)), and so to find initial values which will lead to very different predictions of the profile for different assumed values of \( n \). A second experiment allows easy discrimination of the best value of \( n \) [11].

A particular advantage of this reaction is that the order of reaction with respect to catalyst concentration, \( C_{\text{H}_2\text{O}} \), is easily found. From the o.d.e., writing \( A'C_{\text{H}_2\text{O}}^n \) for \( A \),

\[
\int_{T_0}^{T_f} \frac{d\tau}{(T_f - \tau)^n} \exp(-E/RT) = \int_{0}^{t_i} \left( \frac{C_o}{T_f - T_0} \right)^{n-1} A'C_{\text{H}_2\text{O}}^n \, dt
\]

\[
= \left( \frac{C_o}{T_f - T_0} \right)^{n-1} A'C_{\text{H}_2\text{O}}^n \, t_i
\]

Consider two runs using different values of \( C_{\text{H}_2\text{O}} \) but the same initial values \( C_o, T_o \), and hence the same final temperature \( T_r \). Choose some convenient intermediate temperature \( T_i \) and note the corresponding values of \( t_i \) for the two runs. Now, the LHS is the same for both runs. So

\[
(C_{\text{H}_2\text{O}}^n \, t_i)
\]

is constant too, so that the two pairs \( (C_{\text{H}_2\text{O}}, t_i) \) immediately yield the value of \( n \). As far as is known, this result is new. The values of \( n, m, E, A' \) obtained agree well with the literature [11, 12].

NOTES ON OTHER EXPERIMENTS

The packed tower hydraulics experiment is a conventional study of loading and flooding in two six-inch diameter towers, one packed with Raschig rings and the other with glass helices. However, it has one pleasing feature: the first tower floods first at the top, followed by the flooding moving downwards, whereas the second floods at the bottom and the flooded zone grows upwards. The cause of the former is presumably that the gas volumetric flow is highest at the top; of the latter, that the helices compress readily, so that the bed voidage is least at its base and resistance to flow is highest there. A remarkable number of students don't notice.

The packed bed catalytic reactor is used to study the dehydration of 2-propanol to a mixture of propylene and di (2-propyl) ether over an alumina catalyst: this reaction is only mildly endothermic so that reactor isothermality may be assumed, the reactor and the feed preheater being in an oven. Catalyst particles are so small that pore diffusion limitations do not occur.

The enzyme catalysis experiment is performed in a batch reactor made by modifying a spinning catalyst basket reactor of the Carberry type. Glucose is converted to fructose by an immobilised enzyme "sweetzyme Q" manufactured by Nova A. S. of Copenhagen, used at 60°C and pH = 8.5. The constants in the Michaelis-Menten kinetic expression are determined. The rotational speed of the basket can be varied from run to run to permit investigation of external mass transfer effects.

ACKNOWLEDGMENT

This lab was assembled as a team effort, so

Ccontinued on page 160.
With the increasing amount of published information and improved methods of assessing this information, there is a new awareness within chemical engineering that systematic information retrieval from the literature is an important starting point for any type of project. To match this awareness (already prevalent in industry), chemical engineering courses should include some instruction in the subject of information science.

There is more to information retrieval than simply knowing where the library is and knowing how to use an index. It is possible to give students a more thorough background in information science in a comparatively short course—if it is well organised. The objective of this paper is to indicate the possible contents of such a course and to relate some experiences already gained in teaching the subject to chemical engineering students.

COURSE OUTLINE

A modern information and documentation course for chemical engineers should cover printed bibliographic information, numerical data, and methods of computer retrieval, both of numerical and bibliographic data.

Available Printed Information

Traditional literature searching has always concerned itself with searching the scientific journals—the primary publications. Since chemical engineering is a mixed discipline, it is often worthwhile to look in other specialized areas for relevant material—statistics, operations research, chemistry, mechanical engineering, computing, and electrical engineering all overlap with various chemical engineering subjects, particularly at the research level.

Primary literature goes beyond the published journals; conference pre-prints, dissertations, and patents all belong to the primary literature, but are more difficult to obtain than the international journals. The difficulty in obtaining these very important publications is overcome by the development of the secondary publications.

The secondary publications are abstracts of the primary literature, the most famous of which is Chemical Abstracts. Chemical Abstracts is so important to the chemical engineer that he should be able to use it without difficulty, understanding the concepts of its indexing and registry numbers for components. Chemical engineering has some lesser known abstracts of its own: Theoretical Chemical Engineering Abstracts (POB 146, Liverpool, England), Chemical Engineering Abstracts, (University, Nottingham, England), and DECHEMA, (PF 970 146, D-6 Frankfurt-97, W. Germany). Abstracts in overlapping fields (INSPEC for mathematics and control, Engineering Index for heat exchange) can also be useful.

Under secondary publications one can also list the Science Citation Index (SCI) which enables forward searches to be made, and the ISI weekly publication of contents pages of the scientific journal, Current Contents, enabling the contents of most of the recent journal issues to be effective.
ly followed.

Finally there is the tertiary literature. This is an organised summary of the literature in each particular field: handbooks, monographs, data collections, and textbooks. Perry is, of course, the most important. Then there are the encyclopedias of chemical technology of Kirk-Othmer and Ullmann.

Numerical data are very important to the chemical engineer, and these are generally found in the tertiary publications. General data concerning chemicals are best covered by Beilstein (organic) and Gmelin (inorganic). Though both these works were in German, new editions are now in English. Other publications concentrate on particular properties.

Finally there are the monographs and textbooks. They often provide an excellent starting point for any search by summarizing the particular technology up to a certain point in time—which is often adequate for the needs of many problems.

The graduating chemical engineering student should be aware of these facilities in his library. He should be able to carry out searches in Chemical Abstracts, know where to obtain numerical data, know how to use the subject and author catalogues in the library, and know that the librarian is a trained professional, there to help him when he has difficulties.

Computer-Stored Information

Bibliographic Data Bases: The history of the development of computer readable bibliographic data bases is a fascinating opening to the subject of the production of SDI (Selective Dissemination of Information) tapes. To rationalize the production of the printed abstracts, the total abstracts were coded onto magnetic tape. It was then a small step to the distribution of these tapes to institutions wishing to perform their own searches electronically rather than waiting for the printed versions to be posted and going through them manually!

It is interesting for most chemical engineers to know the principles on which the computer searching is done. The availability of the abstracts on tape, the need to have a thesaurus and to invert the SDI tapes to be able to recover which abstracts refer to each particular keyword are important points to explain in the course.

There is a growing feeling among information scientists that the engineer himself should understand how computer searches are done. The need to choose the individual keywords carefully and to define a suitable search strategy, to know the pitfalls of not including enough alternative descriptions, and to know how to improve the relevance by including further keywords. It is particularly important that the chemical engineer know which data bases are likely to be of most use to him. Surveys in Europe have shown Chemical Abstracts to be the most useful (although it is far from ideal for most chemical engineering problems). Chemical Abstracts needs backing up with COMPENDEX or INSPEC, where appropriate. Besides these three there are many other data bases covering particular areas of use to chemical engineers—part of the NIH-EPA Chemical Information System for safety from Birmingham University. Before joining the Systems Engineering Group of the Technical Chemistry Laboratory of the Swiss Federal Institute of Technology (ETH) in 1971, he spent twelve years in industry. His efforts are toward instigating the sensible use of computers in all branches of chemical engineering. (R)
and chemical properties, DERWENT for patents, PREDICAST for commercial information, DECEMA for equipment design and corrosion problems, etc. The undergraduates should be made aware of the scope and limitations of the various fields.

It is also good for the undergraduates to be informed on the component parts of the computer literature searching system—the abstractors, the files and inverted files, the hosts, the communications networks—that all need paying for every character retrieved. And then, the multitude of languages!

**Numerical Data Banks:** Parallel to computer retrieval of bibliographic data, banks of physical properties for use by chemical engineers have been developing and are now generally accessible by any terminal connected to the telephone network. Most normal chemicals in commerce (±800) are now available on these banks which store numerical physical property data, or use predictive methods to give estimated values for those not available. PPDS, EPIC and DECEMA systems are available in Europe, and PPDS in the US.

For teaching purposes, a number of small demonstration banks exist. CHEMCO is probably the most widespread. There is no better way of making a student realize that these modern tools are available to him than to let him use them during a design project.

Such data banks could be handled in an information and documentation course or in a thermodynamics course, since they are excellent for demonstrating enthalpies, chemical equilibrium, vapour-liquid equilibria (VLE), and equations of state. For them to be handled in both courses would have the advantage of helping integrate the whole curriculum.

**SEARCH PROCEDURES**

There are two fundamental types of literature searching

- **Retrospective searching,** where a comprehensive list of relevant literature published on a special topic is sought

- **Current awareness searching** (SDI = Selective Dissemination of Information), where the interest concerns the current publications on the topic under study.

The selection of information sources and the mode of information retrieval will depend on the type of search. For starting a systematic literature search, the problem and its limitations should be clearly defined. In manual as well as in on-line searches, the effectiveness of the study depends on how well-prepared the search strategy is. To get some experience in strategy preparation and optimization, the library users should practice manual searching techniques before starting on-line searches.

A very useful start for undergraduate students in chemical literature are small search exercises in *Chemical Abstracts* using the printed indexes. The user should become familiar with the Index Guide and the Chemical Substance Index using the *Chemical Abstracts* nomenclature. He should also learn the concept and the limitations of the Registry Numbers. These numbers, characterizing a single, well-defined chemical compound, build a link between different bibliographic and numerical data banks. The user should also practice how to select relevant keywords with all their synonyms and truncations. He should also be familiar with the linking concepts (and, or, not) creating combinations of sets selected by the keywords. For narrowing the search strategy the user should also be aware of other possible limitations such as language, document type, country, or publication year.

Even with all these preparations, electronic information retrieval continues to be a difficult task for the average user without the assistance of information specialists. For example, the *Chemical Abstracts* (CA) SEARCH files are accessible from many host systems such as Lockheed, SDC, or Data Star. However, every host system has its own software and its specific advantages and disadvantages, making different set combinations and search strategies possible. The fine structure of the programs are developing. An average end-user making only a limited number of on-line searches cannot be aware of all the progress made to reduce the search costs. Although development in the direction of "user-friendly systems" is progressing, at the moment the optimal combination seems to be co-operation between the information specialist who knows the information systems and the end-user who knows...
the extent of his information requirements, so that the on-line systems can be used efficiently as an interactive system adapting the search strategy to the given information. This need for teamwork between the information specialist and the engineer is ground enough for the undergraduate engineer to be made aware of the principles of information retrieval.

TEACHING EXPERIENCE

Experience in the Swiss Federal Institute of Technology (E.T.H.)

In common with many other universities, the time-table structure at E.T.H. makes it virtually impossible to introduce new courses, so modern methods of information and documentation have to be squeezed into two hours borrowed from another course, with practical exercises carried out as part of a semester project. The introduction to the semester project enables an additional two-lecture-hours on manual searching to be given. Because the particular semester project is concerned with literature retrieval (four days), the students get ample practical experience on manual searching. The total of four lecture hours (which includes a computer search demonstration) is not really adequate to properly cover the material—six to eight hours would be better. The four-day manual search project is more than necessary for the normal chemical engineering student. However, in the Technical Chemistry Department at E.T.H. there is a strong emphasis on chemistry, which is consistent with extended information retrieval exercises.

The subject would be given more status if it were a short course in its own right, and not simply squeezed into odd hours. This could conveniently be taught together with odd hours given on communication (report writing, specification writing, drawing standards, speaking and lecturing) to provide sufficient material for an independent course on communication.

Undergraduates do not carry out computer searches, but postgraduates are allowed to carry out some of the searches by computer in collaboration with an information specialist.

Experience at the Instituto Quimico de Sarria

Since 1979 the Higher Technical Education Centre for the formation of engineers has provided a course on Scientific and Technical Documentation for the fifth-year students (the last year of the chemical engineering curriculum). It is compulsory for those students who opt for the research course, at the end of which a Trabajo de Fin de Carrera (final report on conclusion of studies) has to be submitted before the degree (in chemical engineering) can be awarded. It is, however, optional for those students who do not go for this research course and who will consequently not complete their studies with this degree.

The course is run for one week with two hours every day, giving a total of ten hours for the presentation of the various topics. The exercises are done on an individual basis outside the regular course time, which means an average extra time requirement of three hours for the practical exercises. In the presentation of the material, emphasis is put on practical application, the importance of one-line systems demonstrated, and extensive use of visual material like slides and transparencies is made. The course contents are remarkably similar to Table 1, which is the proposed curriculum we are recommending.

The experience with this course during the last five years has been highly positive. The students have learned or improved their ability to handle basic documentary sources (like Chemical Abstracts, Beilstein, Science Citation Index). They know the possible ways of using information media in their search for information, how to access them, and finally, and this is very important, they realize the complexity of the process for searching for information and are aware of the assistance available from the specialist in information and documentation.

COURSE CONTENTS

The European Federation of Chemical Engineering has had a Working Party on Information

Continued on page 142.
IMPROVEMENTS IN THE TEACHING OF STAGED OPERATIONS

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The use of computer graphics to aid and improve the teaching of chemical engineering principles is an area of growing interest. Many topics have the potential to be greatly improved by utilizing the special capabilities of computer graphics, with rewards such as greater instructor efficiency and additional aid for educationally weaker students. One such topic is the teaching of staged operations, usually conducted within a separations course. For studies involving distillation—the single most important separation technique—the graphical method of McCabe and Thiele [1] is typically employed due to its conceptually simple formulation. However, the manual calculation of a single McCabe-Thiele plot for one case study is a lengthy and laborious procedure, as any junior will attest! In order to investigate the effect of different design parameters on the resulting column, this time-consuming procedure must be repeated for each new case. The repetition involved is of limited educational value, yet it is most important that the student have a firm grasp of the interrelationship between the various operating parameters, e.g., the reflux ratio and the condition of the feed. The usual result is that a severely restricted number of cases can be studied, with additional limitations on the complexity of the system. The results of other interesting designs must be presented to the student already complete, dulling the sense of discovery that their investigation might have produced. Computer graphics offers solutions to these problems, removing the burden of computational effort while preserving the simple graphical representation which allows a ready comprehension of the situation. These advantages were recognized by Calo and Andres [2]. However, their McCabe-Thiele package was devised around the older technology of direct view storage tube graphics, which is unsuitable for interactive use.

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CHEMICAL ENGINEERING EDUCATION
Computer graphics offers solutions to these problems, removing the burden of computational effort while preserving the simple graphical representation which allows a ready comprehension of the situation.

In the graphics package developed at Cornell, the software was written for a sophisticated vector refresh graphics workstation offering superior interactive capabilities with virtually immediate response to user-interaction. This package was implemented in the fall semester of 1984, and will be used in our separations course.

**DESIGNING THE PROJECT: HARDWARE AND SOFTWARE**

The Computer Aided Design Instructional Facility at Cornell's Engineering School has been described in an earlier publication [3]. Of the graphics workstations available, a vector refresh Evans and Sutherland Multipicture System was chosen for this application since software expertise for this type of system was available within the department. However, the nature of the application is such that it could equally well have been set up on a raster graphics system; indeed, the programs have been structured for such a change if necessary. User interaction with the package was made possible largely through the use of an electronic tablet and stylus (or pen), with a VT100 terminal for alphanumeric input. An electrostatic plotter was available for 'hard copy' output of the contents of the screen, a useful feature for the preparation of homework assignments.

As with the graphics package to represent phase diagrams developed at Cornell [3], the appearance of this software package was carefully conceived so that the design criteria given below would be fulfilled in the most effective and inviting fashion—in other words, in what computer scientists like to call a “top-down” approach. The objectives of the software package were:

- For a complete set of user-supplied variables describing the system, a McCabe-Thiele plot should appear on the monitor’s screen, together with a scaled diagram of the resulting distillation column.
- Interaction with the software package to change any of the design parameters should be easily effected and should produce an almost instantaneous response in recomputing the McCabe-Thiele plot and the design of the column, redisplaying them on the monitor. This interaction should be designed so that qualitative trends in column design resulting from parameter changes could be viewed almost continuously if desired, or that specific values for these parameters could be entered if a quantitative calculation is required.
- Extensive help must be available to aid the confused, while the ability to restore the original screen display is essential for the computationally entangled. Instructive messages should appear on the screen to inform the user of the program's status—for example, if some unavoidable delay in processing the input is about to occur.
- The program must be structured in such a way that its extension to more complex problems can be incorporated into the existing software in a straightforward manner. Thus, some long-range planning of the possible modifications to the package had to be considered.
- As far as possible the software produced should be portable, so thought had to be given to producing a machine-independent code. The decision to write the software in FORTRAN, still the most widely used high-level language in engineering, stemmed from this desire.
- Last, but still important, the programs should be “bomb-proof,” even for the most inventive student user! The most likely input errors, or miskeying, must be anticipated wherever possible.

Should these objectives not be met, resulting in a final product that was difficult or frustrating to use, much of its educational impact would be lost. Such attention to detail in designing the application graphics package is extremely time-consuming in terms of software development, but the effort is amply recompensed once its use is established as a regular component of the course.

**THE INTERACTIVE MCCABE-THEILE Package**

We believe that the final product does indeed meet the criteria given above, satisfying both the instructor's and the student's differing needs. It is a routine matter to produce numerical subroutines performing the calculations for the McCabe-Thiele plots, but more time-consuming to incorporate the graphics software to display an aesthetically pleasing picture on the screen and an ergonomically attractive interaction with the displayed image.

The layout for the display is as shown in Fig. 1. The master object displayed consists of a McCabe-Thiele plot with appropriate equilibrium and operating lines and the “ladder” of stages.
This is supplemented by a scale diagram of the corresponding design for the distillation column (relative to a six-foot tall 'stick figure' standing beside it). Above these diagrams information about the current values of the various operating parameters is displayed, while the space below is reserved for the "menu." The menu provides a selection of options to enable the user to interact with the viewed image. The user may select a particular option by moving the pen across and slightly above the tablet until the cursor (in the form of crosshairs on the screen) lies within the required area (or window) designated for this option. Pressing the tip of the pen down in contact with the tablet activates the window to perform a specific task.

The menu options for interacting with the package are listed below (the window names are in bold face type)

1. Six windows allow input of both the composition and the flowrate of the feed, distillate, and waste product. The program will prompt the user for values of any four independent variables from these six in order to completely define the problem. Values are entered by placing the pen down at some point within the window. Each window contains a potentiometer which allows the value of the appropriate variable to decrease or increase as the pen is moved left or right across the window. The value given by the current position of the pen may be read in the area above the diagrams.

2. When the calculate window is selected, the program checks to see if the mass balance was satisfied by the user-supplied variables. If the mass balance was not satisfied the user is informed and will be prompted to re-enter all four values. In this way the programs assure that the student is capable of performing the mass balance correctly. Assuming all is well, a McCabe-Thiele plot is produced for "start-up" values of the operating parameters, e.g. the reflux ratio.

3. The user may now alter these operating parameters by selecting appropriate windows for the reflux ratio, operating pressure and heat per mole of feed. Again, moving the pen along the length of the window alters their respective values with immediate response from the programs, producing altered images for the McCabe-Thiele plot and column design.

4. If the user desires to set an exact value for any variable this can be done using the key in option. This offers an alternative to using the potentiometers within the windows, which are more suited to observing qualitative trends in the behavior of the McCabe-Thiele plot. The 'key in' feature prompts for numerical input at the VT100 terminal.

5. The reset window sets all the flowrates and compositions to zero and the operating parameters (p, R and q) back to their initial preset values.

6. The window marked economical analysis allows the user to determine the optimum value of the reflux ratio in cost effectiveness. This will be explained in more detail in the following section.

7. Snap triggers the production of a paper copy of the current screen contents on a nearby plotter.

8. Help invokes the display of information pertinent to the operation of each of the windows in turn.

9. Exit halts execution of the program.

COLUMN DESIGN

The McCabe-Thiele method is widely used as an educational tool in teaching distillation column design at the undergraduate level, and details of the method need not be repeated here. In the existing version of the program, a single column involving only one feed of a binary mixture of components is considered. Extension of the programs to multiple feeds and sidestreams is underway. The feed may be introduced into the column...
in any fluid condition (i.e., saturated liquid, subcooled liquid, etc). Antoine's equation is used to obtain the saturated temperatures and pressures of both components, and the x-y equilibrium curve is obtained assuming ideal behavior. Optional consideration of a variety of non-ideal descriptions of the equilibrium curve is also possible.

Routines are included which calculate the diameter and height of the distillation column for each case study in order to produce the scaled diagram described earlier, including the correct number of bubble-cap trays, a total condenser, reboiler, and the location of the feed tray. This is achieved by following the recipe outlined in Treybal [4].

Some interesting aspects of column design with regard to the economics involved are also incorporated by allowing the preparation of a graph showing the relationship between a given reflux ratio and the total cost involved, considering both capital costs and estimated running costs over the expected lifetime of the column. The minimum of this parabolic curve allows the estimation of an optimum reflux ratio for the most cost-effective operation of the column.

SUMMARY

The implementation of the computer graphics package described has proved to be of considerable assistance in the teaching of staged operations. Instructors benefit from the increased quantity and complexity of problems which can be investigated in the allotted time, and students welcome this novel and easy-to-use tool which makes completing their assignments so much less onerous.

ACKNOWLEDGMENTS

M. G. would like to thank C. D. Naik and G. Charos for many helpful discussions. It is a pleasure to thank the Gas Research Institute for practical support of this work.

REFERENCES


ChE letters

More on Tubular Flow Reactors

Dear Editor:

Professor Asfour's two improvements (CEE XIX, 2, 84, 1985) to the original design of a tubular flow reactor using crystal violet dye and sodium hydroxide reactants (Hudgins and Cayrol, CEE XV, 1, 26, 1981) are timely ones. This experiment, to judge from a recent survey (E. O. Eisen, "Teaching of Undergraduate Reactor Design," AIChE Meeting, San Francisco, Nov. 1984), is now incorporated into several reaction engineering laboratory courses in North America.

I welcome the occasion of the Asfour article to suggest several additional improvements that arise out of our experience since 1981.

First, I concur with the footnote in the Asfour paper. Tygon tubing is an unhappy choice for the tubular reactor. In our experience, clear Tygon tubing darkens within a few hours' use to a permanent deep violet. This obscures the pleasing axial color change that is one of the main attractions of the experiment. Polyethylene tubing, though translucent rather than transparent, resists the crystal violet dye for a much longer time.

Calculating the reactor volume can be a problem. Certainly, the nominal value of the inside diameter of the tubing is not sufficiently accurate. Some students have improved on this value by trying to fit the tubing using indexed drill bits. Because of the flexibility of the tubing, however, it is not certain that the cross-sectional area remains undistorted when the tubing is wound on the large spool. Weighing the spool with the reactor tubing empty and then filled with water appears to be the most rigorous way to obtain the volume.

In both of the above CEE articles, the spool is shown mounted on its side. This has proven to be an unfortunate method of mounting since bubbles often enter the reactor tubing (perhaps from the mixer pump), become trapped in the coils of the tubing, and grow. An effective remedy is to remount the spool with axis perpendicular to the lab bench and flow spiralling upward. Of course, this does not eliminate bubbles but does prevent their retention and growth sometimes to several percent of the total reactor volume.

Continued on page 161.
SOME OF THE BASIC methods of chemical engineering (heat and mass balances, for example) have analogies (such as money) in everyday life, and freshman students rarely have any conceptual difficulty when such basic ideas are introduced. However, when heat and mass balances are combined with recycle, students often have difficulty in analysing the process. They have difficulty not so much with the heat and mass balances themselves as with the whole concept of the recycle process. This is mainly because there is no immediate everyday counterpart, although analogies can be attempted with taxis and people.

In order to aid the understanding of recycle we have devised a simple apparatus in which water is heated in a recycle loop. When operated in the steady state, the apparatus permits both a visual and an experimental appreciation of the operation of a simple recycle loop. Moreover, in the unsteady state the apparatus has a response time of ten minutes or so, and thus, transient behaviour can be followed easily. The apparatus is relatively simple, and since it is built from domestic plumbing pipes and fittings it has a familiar and easily grasped appearance. It is mounted on a wallboard so that the flow path can be seen at once. It uses only water and electricity as consumables.

APPARATUS

Fig. 1 is a schematic diagram of the apparatus. The recycle is driven by a domestic central heating pump of the type used to circulate water around radiators. Ours is an SMC Commodore and it consumes about 150 watts. The heater is a modified instantaneous shower heater, in essence a copper can containing a 3kW heating element. The shower heater originally had two in-built safety devices, one a water pressure switch and the other an anti-scald thermal cut-out. The heater could only be activated when there was pressure (and hence water) in the can and the temperature was below 50°C. We modified our heater to increase the cut-out temperature to 80°C and removed a flow constriction in the pressure-sensing circuit.

The pump drives the recycle at up to 8 litres/
To RECYCLE

FIGURE 1. Schematic diagram of the apparatus. The inlet flow, \(Q\) (maximum 3 litres/min), is ordinary mains water. A recycle loop, flow \(q\) (maximum 8 litres/min) is driven by a pump through a domestic shower heater (3kW). The temperature of the inlet water, the outlet water and just after the heater in the recycle loop, are all measured.

\[ T_1 = T_0 + \frac{H}{QC} \]  

(1)

where \(H\) is the combined heat input of the pump and heater and \(C\) is the specific heat capacity of water.

Similarly one obtains

\[ T_2 = T_0 + \frac{H}{QC} + \frac{H}{qC} \]  

(2)

from a heat balance across the shower heater, after eliminating \(T_1\) by means of Eq. (1).

So, by measuring the outlet water temperature, \(T_o\), as a function of the throughput flow rate, \(Q\), it is possible to determine the combined heat input of the heater and pump by the use of Eq. (1). The experiment takes some time to perform because it takes about fifteen minutes for the steady-state to be reached after a change in flow rate. By plotting \((T_1 - T_o)\) against \(1/Q\), the gradient \((H/C)\) gives the power input \((H)\) as shown on Fig. 3. Alternatively, Eq. (2) can be used. In

FIGURE 2. A photograph of the apparatus. It is mounted on a wall board so that the flow directions are obvious. The top pipe is slightly angled to assist in purging the air which comes out of solution as the water is heated.
FIGURE 3. Results from the steady-state operation of the apparatus. The temperature rise of the through stream is plotted against the reciprocal of the through flow rate. The graph is a straight line through the origin with a gradient determined by the combined energy input of the heater and circulating pump.

this case $T_2$ is plotted against $1/q$, where $q$ is the recycle rate, and $H$ is obtained from the same gradient. This latter method has the advantage of actually making use of the recycle flow.

Unsteady-State

In unsteady-state experiments both the inlet flow and recycle flow are fixed, the system is allowed to approach, but not necessarily reach, equilibrium, and the heater is switched either on or off as appropriate. The apparatus takes several minutes to respond and the dynamic changes can be monitored by hand. Typical examples of temperature-time graphs are shown in Fig. 4 for both rising and falling temperature. The recycle rate was 5 litres/min and the inlet flow rates 1.0, 1.5, 2.0, 2.5, and 3.0 litres/min.

A heat balance on the system for a small time interval, $dt$, in which the outlet temperature, $T$, changes by $dT$ gives

$$QCT_0 + H = QCT + VC \left(\frac{dT}{dt}\right)$$

where $V$ is the volume of the recycle circuit which, as an approximation, is assumed to be perfectly mixed. Using Eq (1) to eliminate $H$, and then integrating from $T_0$ at time 0, gives

$$\ln \left[ \frac{(T_1 - T)}{(T_1 - T_0)} \right] = -\frac{Qt}{V}$$

$T$ thus rises exponentially to the steady-state temperature $T_1$ when the heater is switched on and falls exponentially to the temperature $T_0$ when the heater is switched off. The time constant is independent of the heater power and also of the recycle rate but depends on $Q$, the inlet flow rate, and the volume of the system. By plotting the log arithmetic term of Eq. (4) against time, the gradient $(-Q/V)$ can be determined. If this is repeated for several flows then a graph of these gradients against $Q$ gives a straight line of slope $1/V$ through the origin.

The volume of the recycle circuit so determined is only an effective volume rather than a
true internal volume because the metalwork of the system behaves as a heat sink. Its effect is quite large because the pump weighs several pounds but conduction is fast enough for the metal and fluid in the recycle loop to have the same temperature. The temperature profiles of Fig. 4 demonstrate that, as predicted by Eq. (4), the system reaches equilibrium faster for higher inlet flow rates than it does for lower inlet flow rates.

Figure 5 shows the straight lines given by Eq. (4) for rising temperature using the typical data given in Fig. 4. Note that there is a delay of between 10 and twenty seconds before the thermometer responds to the heater being switched on, due to the transit time of the water in the pipes. Fig. 6 shows the gradients of the lines of Fig. 5 plotted against $Q$, the inlet flow rate, and it is from the gradient of Eq. 6 that the effective volume, $V$, of the recycle loop can be determined.

FIGURE 5. Logarithmic plots of the results of Fig. 4(a).

FIGURE 6. The effective volume of the recycle system determined from the gradients of the lines in Fig. 5 by plotting the gradient against the through flow rate. Values from the curves of Fig. 4(b) are also shown although the straight line logarithmic plots have not been reproduced.

REFINEMENTS

The analysis of the behaviour of this apparatus is straightforward. The accurate interpretation of actual experimental results is not so simple because of drift in the temperature of the water feed and other small effects. Rough and ready results and analysis may be adequate for routine teaching, but to get the best from the apparatus a more refined approach is necessary. For example it is better to extrapolate the dynamic experimental data to obtain the steady-state temperatures. This gives students useful practice in analysing an exponential rise to a limit as well as giving the steady-state temperatures more accurately. The falling temperature curves give limiting temperatures which, because of the heat input from the recycle pump, are not equal to the inlet water temperature $T_0$. Indeed the temperature rise between the inlet water temperature and the extrapolated outlet water temperature with the heater switched off can be used in a heat balance to determine the energy input by the pump. Fig. 7 shows $\Delta T$, the temperature rise of water through Continued on page 143.
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 that elucidate difficult concepts. Please submit them to Professor H. Scott Fogler, ChE Department, University of Michigan, Ann Arbor, MI 48109.

ONE MONTH PROBLEM...

An Exercise in Modelling

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In applied mathematics courses the emphasis is usually on solving equations. There is very limited discussion about problem-definition and expressing it in terms of mathematically understood phenomena. A mathematically understood phenomenon is one which, at least in its simplest form, can be expressed mathematically [1]. Once the problem is interpreted, it requires only the substitution of symbols for words before a relevant equation is obtained. Teaching this missing part of the story is difficult because it is a creative process. There are no set procedures available for such an exercise. The students can, at best, be helped to learn by themselves. With this in view, in a course entitled “Applied Mathematics in Chemical Engineering,” the students are given a ‘one month problem.’ The problem is a real life situation which has to be defined in such a way that it can be expressed and analyzed mathematically.

The students are encouraged not to get into complicated mathematical formulations. This strategy helps the students to concentrate and to appreciate the subtle nuances involved in problem definition and modelling strategies. Thus the scope of the ‘one month problem’ is limited and should not be confused with the regular modelling exercises. Wherever possible, the simple model obtained is evaluated against the existing data. Near the end of the semester the problems are assigned to the students (one each) as a project, to solve as regular modelling problems. One such problem is discussed below.

Problem

You are going to spend the winter in the middle of nowhere, say in the Himalayas or in Alaska, where the temperature gets very cold. You are going to stay in a cabin where there is no heating. How will you decide whether the sleeping bag you have will keep you warm enough or comfortable?

Solution

The best way to find out is to ask somebody who has experienced the same climate. In the absence of an experienced person, however, we have...
to resort to mathematical modelling to determine how much insulation is necessary to keep the body warm and comfortable. Before we proceed with the solution, the term “comfort” has to be defined in the context of the problem.

“Comfort” depends largely on the skin temperature. When the skin temperature is high, sweating begins and the latent heat of evaporation cools the body down. It is very uncomfortable when one starts sweating inside the sleeping bag. Hence the temperature at which sweating begins marks the upper limit of the “comfortable” skin temperature, which is 34.5°C [2].

The skin temperature begins to fall when the skin is exposed to cold temperature. The self-defense mechanisms of the human body try to maintain the skin temperature; however the compensatory measures fail below 32°C, which is known as the shivering temperature [2].

As long as the skin temperature is between the sweating temperature and the shivering temperature the person feels comfortable, i.e.,

\[ T_{sw} > T_s > T_{sh} \]

where \( T_{sw} \) = the sweating temperature
\( T_s \) = the skin temperature
\( T_{sh} \) = the shivering temperature.

From the above discussion the problem can be redefined as follows: At a given outside temperature, calculate the insulation necessary to maintain the body temperature between shivering and sweating temperatures.

The following assumptions are necessary to make the problem mathematically tractable

- The heat production rate is at \( q \text{ kcal/m}^2\text{-hr} \) and the skin temperature is uniform throughout.
- The loss of heat by convection, radiation, and evaporation is negligible, and the heat is lost only by conduction.
- The air pocket between the sleeping bag and the body is neglected.

Let us assume the body is rectangular in cross section, and a sleeping bag of thickness \( t \) is covering it uniformly as shown in Fig. 1(a). Since the skin temperature is uniform throughout, a simple one-dimensional model is sufficient to describe the system, as shown in Fig. 1(b). Under steady state conditions the rate at which heat is pro-

![Figure 1](image1.png)

![Figure 2](image2.png)
<table>
<thead>
<tr>
<th>AGE</th>
<th>MALE</th>
<th>FEMALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>45.0</td>
<td>43.0</td>
</tr>
<tr>
<td>20</td>
<td>39.0</td>
<td>35.0</td>
</tr>
<tr>
<td>30</td>
<td>37.0</td>
<td>35.0</td>
</tr>
<tr>
<td>40</td>
<td>36.5</td>
<td>35.0</td>
</tr>
<tr>
<td>50</td>
<td>35.5</td>
<td>34.0</td>
</tr>
</tbody>
</table>

It can be easily shown that the required thickness does not change with various age groups as the heat production rate is not significantly different (Table 1). In cases where the ground temperature is cooler than the atmospheric temperature, we can make a conservative estimate of the bag thickness by taking both the ground temperature itself as the surrounding temperature and the thermal conductivity of the compressed packing material.

It was found that the assumption of cylindrical shape for the body does not alter the result significantly.

ACKNOWLEDGMENT

Contributions of Umesh K. Jayaswal, Atul Bansal, and V. L. N. Murthy are gratefully acknowledged.

REFERENCES


INFORMATION TRAINING

Continued from page 131.

and Documentation in existence for a number of years, with the objective of assisting the introduction of new methods into the chemical engineering profession. As part of this work they have developed a suggested curriculum for a course in information and documentation for chemical engineers. This is given as Table 1. This table could be taken as the basis for any new course developed for chemical engineers.

CONCLUSIONS

The aim of this paper has not been to give a quick course on information and documentation, but simply to mention the trends in this quickly moving area and to indicate that there is sufficient material relevant to a chemical engineer to form a short course on the subject. If the reader is left confused, but impressed, then we have achieved our aim and suggest he get together with his own information scientist (librarian) to develop a course for his undergraduates.

We believe a course of about nine to twelve hours would be ideal. This would enable about three hours of exercises in the library to be made and a computer retrieval demonstration to be attended. If this amount of time is not available, then two hours of lectures could survey the material and practical experience could be gained

TABLE 1

<table>
<thead>
<tr>
<th>SOURCES OF INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed</td>
</tr>
<tr>
<td>a) Primary Sources: Journals and reports, conference reprints, patents, dissertations.</td>
</tr>
<tr>
<td>b) Secondary Sources: Chemical, Chemical Engineering and Engineering Abstracts; SCI.</td>
</tr>
<tr>
<td>c) Tertiary Sources: Handbooks, encyclopedia, books. Advances in . . . List important ones.</td>
</tr>
<tr>
<td>Computer Data Bases</td>
</tr>
<tr>
<td>a) Bibliographic data bases.</td>
</tr>
<tr>
<td>b) Numerical data banks.</td>
</tr>
<tr>
<td>SEARCH PROCEDURES</td>
</tr>
<tr>
<td>b) Computer Searching: Bibliographic: files, networks, host computer; data base selection; searching techniques; costs</td>
</tr>
<tr>
<td>Numeric Data Bases: available banks; procedure, cost</td>
</tr>
<tr>
<td>c) The role of libraries and information scientists in association with laboratory work and project work. At least, practical experience should be planned and guided—not simply left as a random search for the student to undertake when all else has failed.</td>
</tr>
</tbody>
</table>

ACKNOWLEDGMENTS

The authors wish to express their thanks to those members of the E.F.C.E. Working Party on Information and Documentation who commented on the draft outlines of this paper. Their comments were gratefully received and incorporated
REFERENCES


RECYCLE WITH HEATING
Continued from page 139.

the apparatus, plotted against 1/Q. The energy input of the pump is found from the gradient to be about 210 watts. The intercept (about 0.3°C) probably represents the scale reading difference between the two thermometers.

A further refinement that is possible with the apparatus is to run the dynamic experiment in the limiting case of recycle with no through-flow. With no through-flow the apparatus is analogous to a well-mixed batch reactor, whereas it is analogous to a CSTR when through-flow is present. Fig. 8 shows results for this case for three different recycle rates. The three lines do not coincide because different starting temperatures were used. The results show that after 30 seconds or so there is, as expected, a linear temperature rise with time. The temperature rises with no limit at least until the safety cut-out of the shower heater operates. The gradients of the lines on Fig. 8 are all the same and by using the combined heater and pump energy input of 3.21 kW it is possible to estimate the effective recycle volume.

This is 3.95 litres for the results shown, about 5% less than the value obtained using the through-flow method. The most likely cause is the time taken to heat up parts of the metalwork of the pump; this experiment lasts only four minutes, compared to ten for the through-flow method.

Students always say that the apparatus could be improved by lagging the pipework to reduce heat losses, but simple measurements on a cooling curve indicate that the heat losses are very small. Also, for some of the temperature response curves the water temperature is below the ambient air temperature and so the system is gaining heat rather than losing it.

CONCLUSION

Our apparatus has been in service for several years without giving trouble, perhaps a consequence of using well proven domestic components. The recycle experiments performed with it can range from simple mass and heat balances right through to the dynamics. Its main purpose, however, is to provide a vivid demonstration of basic mass and heat balances in a system with recycle.

FIGURE 8. With no through-flow the recycle loop temperature rises without limit as can be seen above. Using the combined energy input of the heater and pump (determined on Fig. 3) the effective volume of the recycle loop can be determined using the gradient of the lines. This volume can be compared with the value determined on Fig. 6 (4.17 litres equivalent). The lines are for different recycle rates which, as expected, have no effect. Different initial temperatures were used. Up to the first minute it can be seen that the system is not well-mixed.
IMPACT OF PACKAGED SOFTWARE FOR PROCESS CONTROL ON CHEMICAL ENGINEERING EDUCATION & RESEARCH

BRIAN BUXTON
Teesside Polytechnic
Middlesbrough, United Kingdom

In August 1982 the Department of Chemical Engineering, Teesside Polytechnic, UK, took delivery of a Ferranti Argus 700GL process control computer system. The system was supplied in accordance with a detailed enquiry specification which defined precisely the objectives and scope of the system (Table 1). The objectives of the system are

- To assist departmental research into varied chemical engineering topics by providing a comprehensive and flexible data logging and plant control system
- To provide a teaching facility for the department

The availability of packaged software transforms this situation, enabling the engineer (student or practitioner) to produce useful process control software in a matter of days rather than months.

by live demonstrations of plant monitoring and control applications, simulation, and implementation by students of control strategies.

It is now timely to report on the extent to which these objectives have been realised. At the time this paper is being written, the system is capable of controlling two pilot plants and has also been substantially integrated into our teaching programmes. Computer control is now taught

| TABLE 1 |
| Enquiry Specification |

1. Objectives and scope of the system
2. Extent of supply
3. Exclusions from supply
4. Functional specification
   - Data acquisition
   - Data logging
   - Pilot plant control
   - Operator interface
   - Data links
   - Development facilities
   - Teaching facilities
5. System hardware configuration
   - Configuration
   - Equipment specification
   - Control system description
   - Maintenance facilities
   - Availability/reliability
6. Supply of software
   - Standard systems software
   - Standard packaged application software
   - Special to project software for a) plant control
     b) data links
   - High level language
   - Operator facilities
7. General electrical & electronic design requirements
   - Management/engineer facilities
   - Failure/recovery
   - Expansion capability
8. Acceptance tests
   - System hardware/software
   - Packaged software
   - Application software
   - System robustness
   - System loading
9. Installation and commissioning requirements
10. Documentation
11. Project time schedule
12. Maintenance and training requirements
13. Project management
   - Project organisation
   - Project communications and control
14. Commercial requirements

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Brian Buxton is a senior lecturer in the Department of Chemical Engineering, Teesside Polytechnic, UK. He studied at the University of Aston in Birmingham, receiving his BSc degree in 1967 and his PhD in 1971. He spent 10 years in industry with both ICI and the British Steel Corporation. During this period, he was responsible for the specification, installation and commissioning of several computer control systems. He joined Teesside Polytechnic in 1981 and was responsible for the specification and procurement of the Ferranti Argus computer control system featured in this article. His research interests include the implementation of adaptive control techniques on chemical processes.

in all the higher education courses offered by the department

- Higher Diploma
- BEng Honours Degree Courses
- Post Graduate Degree Courses (MSc and PhD)

as well as providing a key facility for our postgraduate research teams.

It is emphasized that all the teaching programmes involve a substantial proportion of practical experience on the computer system coupled with live demonstrations of on-line computer control. It has been found that this new approach to teaching process control stimulates considerable interest from the students who are readily able to relate to these practical situations. Furthermore, the experience gained on such systems is much more directly applicable to the industrial environment than the classical control theory or the modern control theory commonly taught in higher education courses.

The configuration of the computer system is illustrated in Fig. 1 and defined in Table 2. Sufficient industrial interface equipment has been purchased to enable the system to control several pilot plants simultaneously. It also provides connection to simulation equipment.

The simulation equipment facilitates both teaching and testing of research software. The monochrome VDU's may be sited alongside pilot plants to provide local operator display and control facilities. Software development may also take place at these locations if required. Further colour graphics terminals will be added to the configuration in the future.

The pilot plants are accommodated in three module rooms. These rooms extend from the ground to the top floor of the building and can ac-

![Computer System Configuration](image)

**TABLE 2**

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argus 700 GL processor</td>
<td>1</td>
</tr>
<tr>
<td>Semiconductor stores (256 Kb)</td>
<td>2</td>
</tr>
<tr>
<td>Monitor and control console</td>
<td>1</td>
</tr>
<tr>
<td>Monochrome VDU's (15 inch display heads and keyboards)</td>
<td>5</td>
</tr>
<tr>
<td>20 inch colour monitor and functional keyboard</td>
<td>1</td>
</tr>
<tr>
<td>Matrix printers (180 cps)</td>
<td>2</td>
</tr>
<tr>
<td>Keyboard for printer</td>
<td>1</td>
</tr>
<tr>
<td>Plus drive cards for all peripheral devices and serial input/output cards</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STORAGE MEDIA</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twin cartridge disc storage system (10 Mb) (one exchangeable, one fixed)</td>
<td>1</td>
</tr>
<tr>
<td>Twin floppy disc storage system (1.0 Mb)</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INDUSTRIAL INTERFACE EQUIPMENT</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogue inputs</td>
<td>176</td>
</tr>
<tr>
<td>Analogue outputs</td>
<td>72</td>
</tr>
<tr>
<td>Digital inputs</td>
<td>64</td>
</tr>
<tr>
<td>Digital outputs</td>
<td>64</td>
</tr>
<tr>
<td>Pulsed digital outputs</td>
<td>8</td>
</tr>
<tr>
<td>Plus usual power supplies, fans, packaging, etc.</td>
<td></td>
</tr>
</tbody>
</table>
commodate large column type processes. A pair of reactor bays is also provided on each floor of the building. Multicore cables have been laid to link the computer to pilot plants in all of the above locations.

CONTROL PACKAGES

The standard system software P.M.S. (Process Management System) encompasses all the facilities required to implement, operate, and manage a computer controlled process. Software packages have been provided by the computer manufacturer which greatly assist the engineer in building the application software required to operate his particular plant. It is this facility which enables the teaching of the subject within the time scale and context of a higher education course.

Prior to the availability of control packages, the general approach of computer system suppliers was to provide “tailor made” software for a specific application in the form of a so-called “turn key” contract. The software was written in a real-time high level language such as CORAL. This meant that engineers were either required to learn in depth a high level language and the associated operating system of the host computer system, or to define their system requirements to a programmer, who in turn implemented the required functions in software. Either of these options was time consuming, costly, and therefore inefficient. The time scale required to learn such programming skills can be measured in months, rather than weeks, of dedicated work, which makes it impossible for it to be incorporated as part of a higher education course.

The availability of packaged software transforms this situation, enabling the engineer (student or practitioner) to produce useful process control software in a matter of days rather than months.

Specifically, the packages assist the engineer in implementing the following functions in software

- Interfacing of plant signals to and from the computer
- Continuous control
- Sequence control
- Operator interface: a means of display and modification of process and control information.

All are clearly essential for the commissioning of any computer control system. The packages are based on the principle that certain operations are common to all process control applications, while the order in which they are applied is specific to the particular application in question.

The task of the engineer is then to select which operations are needed for a specific case and to link them together accordingly. The package provides considerable assistance with this linking “construction" by providing a conversational facility for the engineer in the form of displayed messages (prompts). The task is then reduced from one of detailed programming to one of deciding on a control strategy and then defining a series of operations and associated parameters to implement the strategy. Thus, virtually no programming skills are required and the problem of programming errors which normally arise in the programming of complex software is largely avoided.

TEACHING PROGRAMS

In the context of control packages, the teaching of control system design, from initial strategy to implementation and testing of software using hardware and software simulators, is entirely practicable.

Every opportunity has been taken to incorporate our computer control facilities in our teaching programmes. These include

- Laboratory Practicals for the Higher Diploma
students: e.g., interfacing of plant measurements. This requires that the student generate the software to condition and convert electrical signals into engineering units. The operation of the software is then tested by means of simulation panels.

- Short Course (10h) for the final year of the BEng course. The course includes several practical sessions on building software to interface signals, continuous control loops, and operator displays. The project used to assess the students in the current academic year requires that the students work as a project team to generate the entire software to monitor, data log, and control a fermenter. The facilities will include sequence control of the plant and a colour graphic display of the process providing a live mimic of the plant operation. This is no artificial project since the software produced by the undergraduates will ultimately be used by the department’s biotechnology research team to implement computer control on a newly acquired fermenter.

Mention should also be made of the allocation of a limited number of research projects to second-year degree students which involve the computer control of laboratory scale apparatus. Current projects involve the control of pH and level.

Chemical engineering also offers service teaching to other Polytechnic departments. The opportunity has, therefore, been taken to offer computer control of a pilot plant as a case study. This academic year, students from both the Computer Science Department (Information Technology MSc Course) and the Department of Electrical, Instrumentation and Control (BSc2), have received a concentrated study on computer control of a specific pilot plant. Like the other courses offered, the courses include a substantial proportion of practical experience on the computer system and live computer control demonstrations.

POST GRADUATE RESEARCH

With regard to research, the main thrust has been directed toward the commissioning of direct digital control of a gas absorption column. This work involved the use of adaptive control (the self tuning regulator) which has been used to optimise the operation of a cascade loop on the column. This research is reported in a separate paper [1] and will not be considered further here. However, it is worth noting that the speed with which this research was implemented owes a great deal to the availability of packaged software on the system. While the self tuning regulators were in fact programmed in a high level language, the interfacing of this software with the control packages (which are responsible for all other control facilities) was straightforward and rapidly achieved. It should be noted that apart from this one specialized application, all our software requirements to date have been easily implemented by the control packages.

Future research effort will be directed to the implementation of computer control on a novel catalytic reactor which has been developed within the department over a number of years [2]. The control system will facilitate prolonged operational runs and assist in further research into commercial application and scale up of this unique reactor. The plan is to apply the adaptive control techniques (recently proven on the gas absorption column) to this reactor. This process lends itself particularly well to these techniques in view of its time varying nature due to the decaying catalyst. This is the main target for the research team.

In conclusion, it is clearly important to recognise the potential of packaged software in the teaching and research environment. (There are also considerable implications for the industrial applications, but that is beyond the scope of this paper.) Packages are rapidly gaining recognition as vital tools for the modern chemical engineer. In an environment of continuously falling computer hardware costs, coupled with the ever-rising costs of producing “tailor made” software, it is essential that the engineer makes full use of commercially available packages. The cost of plant design, implementation and operation of chemical processes and their associated automation systems can be considerably reduced by judicious use of Continued on page 161.
ESTIMATION OF FLUID PROPERTIES AND PHASE EQUILIBRIA

M. HERSKOWITZ
Ben-Gurion University of the Negev
Beer-Sheva, Israel

Numerical values of physical, thermodynamic, and transport properties of pure compounds and mixtures are necessary for the development of chemical processes and the design of chemical plants. Experimental data available in the literature are limited but the need for the estimation of such properties is crucial in calculations carried out by chemical engineers. The study of correlations for estimating various properties is an integral part of courses in transport phenomena and thermodynamics.

Considering the importance of the subject, a course designed to cover the theoretical and practical aspects of properties estimation was introduced into the curriculum. The course is given to junior and senior students who have a strong background in thermodynamics and transport phenomena.

Throughout the course, two fundamental methods for estimating properties are emphasized:

- Corresponding states principle (CSP)
- Equations of state (EOS)

Another method is the group contribution method. This approach is used for estimating thermodynamic properties of ideal gases (no intermolecular forces) and also for estimating critical points of pure compounds [1] and activity coefficients in the liquid phase [7].

The outline of the course is listed in Table 1. Since this field is very dynamic, the outline is updated every year according to new developments.

All correlations and samples of calculation are organized in a manual distributed to the students. During the lectures the theoretical basis of the correlations is discussed and the advantages and disadvantages of various correlations are pointed out.

In the first lecture the students receive a list of primary, secondary, and tertiary literature sources which are useful during the course. The book of Reid et al [1] is recommended as an excellent reference to correlations published until 1976. Other books [2, 3, 4] are used as references to the theoretical basis in properties estimation. The proceedings of the International Conference on Phase Equilibria and Fluid Properties [5, 6] are also valuable references. The students are encouraged to read original papers in order to gain some insight into the limitations of the various correlations.

The material studied during the course is practiced in homework problems which include applications of the correlations. For this purpose computer programs are available in topics such as:

- Phase equilibria calculations by the UNIFAC method
- Phase equilibria calculations by EOS
- Calculation of critical points of mixtures

Some of the programs were provided by Rasmussen [8].

The students are also required to work on a project. Each student selects a certain property and prepares a report which includes:

- A literature search that covers a period of the last three years, based mainly on Chemical Abstracts
but also on current journals.
- Selection of two papers dealing with general correlations, a summary of the basic approach, and the conclusions.
- Selection of a limited database from the literature for testing the correlations. Only primary sources are used with proper estimation of the experimental accuracy of the data.
- A comparison of the correlations and practical conclusions.

Working on this project, the students gain experience in the literature search, the understanding of correlations, and their proper applications.

**Table 1**

Course Outline*

INTRODUCTION: 5 Lectures**
- a. Corresponding states principle (CSP): theoretical background [2, 9]
- b. Classification of fluids: simple, normal, polar and quantum [9]
- c. Critical points of pure compounds: Lydersen [1], Ambrose [10]
- d. Equations of state (EOS) [11]: cubic EOS, the virial EOS, mixing rules
- e. Critical and pseudocritical properties of mixtures, mixing rules

PHYSICAL AND THERMODYNAMICAL PROPERTIES: 18 Lectures
- a. Molar volume of gases and liquids
  1) CSP: Lee-Kesler [12], Teja et al [13]; COS-TALD [14], Gunn-Yamada [1] for liquids
  2) EOS: Redlich-Kwong [1], Soave-Redlich-Kwong [1], Peng-Robinson [15]
  3) Virial EOS: Tsonopoulos [1], Hayden-O'Connell [16], Orbey-Vera [19]
- b. Enthalpy, entropy, fugacity, and heat capacity
  1) CSP: Lee-Kesler [12], Tyagi [20]
  2) EOS: RK [1], SRK [1], PR [15]
- c. Construction of diagrams such as the Mollier diagram

PHASE EQUILIBRIA—VLE, LLE, SLE, GAS-SOLUBILITY: 9 Lectures
- a. Theoretical background [2, 3]
- b. EOS [3]; SRK [1], PR [15]

TRANSPORT PROPERTIES: 10 Lectures
- b. Viscosity: Reichenberg [1], Ely-Hanley [21]
- d. Diffusion coefficients: Wilke-Chang [1], Scheibel [1]

This is also an opportunity to test the reliability of experimental data. Some projects have yielded interesting results which stimulated further research.

The course is a good opportunity to review and emphasize the practical aspects of fundamental principles in thermodynamics and transport phenomena. Five classes of students have already completed this course. They found it useful in practical courses such as plants design, unit operations lab, and the senior project. Furthermore, it provides some of the tools a practicing chemical engineer needs.

**References**

8. Rasmussen, P., Private communication (June 1983).

*Only part of the references are listed.
**Each lecture lasts 50 minutes.
THE CHEMICAL ENGINEERING Program has recently been introduced into the Department of Applied Mechanics and Engineering Sciences (AMES) at the University of California, San Diego (UCSD). The first courses in chemical engineering were offered in the fall of 1979. The strategy was to integrate the new discipline into the previously existing engineering curriculum (fluid mechanics, thermodynamics, engineering mathematics, etc.) while gradually introducing traditional chemical engineering courses. A genuine chemical engineering program was achieved in the fall of 1982.

Initially targeted as one of the major priorities was the establishment of a chemical engineering undergraduate unit operations laboratory to be given at the senior level. We also determined at an early stage that we should develop the innovative skills of the students and not follow the typical cookbook recipe formats so prevalent in many chemical engineering departments. During the past four years, the laboratory has evolved as a setting in which our seniors refine the classroom skills they have acquired and attack problems under circumstances similar to industrial experience. Under space, faculty, and financial restraints typical of many academic programs, we have developed what we feel is a unique approach. The Chemical Engineering Process Laboratory is taught at the senior level over two quarters, and has proven to be successful for a class size under forty, with the involvement of two faculty members and a teaching assistant.

PHILOSOPHY

Our main goal is to provide an environment in which the students have a large degree of control over the direction of their work. Students are skilled at following instructions and obtaining solutions to well-posed problems, situations which are not likely to occur in industry. We would like them to develop the ability to formulate a problem in process analysis and design, design and perform...
experiments to elucidate the problem, analyse the data and present pertinent results in a concise form, and draw conclusions in support of recommendations of further action.

STRUCTURE

The structure of each lab group is similar to that of an industrial process research and development group, with a project head (faculty advisor), group leader and group members, and technical support staff. A fairly general problem statement is presented by the project head and the students are instructed to arrive at the “best solution” to the problem given constraints in funds, equipment, and time (ten weeks). An example of a typical problem statement is shown in Fig. 1. (Blax/Beech, Inc. is a pun on Black’s Beach, a local nude beach and prime surf spot.)

The students are expected to outline an experimental approach to the problem, design and build the necessary experimental apparatus, perform appropriate experiments, and analyze the data. The design and construction process includes selection of material, pumps, valves, fittings, etc., and interaction with the technical support staff who do most of the machining. The lab group also has to select appropriate analytical and measuring devices (e.g., gas chromatograph, viscometer, pH meter, thermocouples, etc.), as well as proper data acquisition procedures (e.g., IBM PC with A/D card, multichannel DVM, strip chart recorder, etc.). Once they have selected a device, the students are expected to learn from instruction manuals provided by the manufacturers, and to perform all necessary calibrations. No exceptions are made with the more expensive equipment such as gas chromatographs, a Brookfield viscometer, or IBM personal computers. The technical staff is available for consultation but only intervenes when procedures undertaken by students may endanger the equipment or themselves.

During the planning phase, the students are encouraged to contact local industry for ideas, and to consult equipment manufacturers and field representatives when necessary. They are also urged to examine and keep abreast of the current research literature in their problem area over the project duration. During the second quarter of the laboratory, they are encouraged to apply what they have learned in computer-aided design and process design courses to the modeling and design of their experiments.

SUMMER 1985

During the past four years, the laboratory has evolved as a setting in which our seniors refine the classroom skills they have acquired and attack problems under circumstances similar to industrial experience.

Blax/Beech Inc.
Design Consultants to the Chemical Process Industries
La Jolla, California

Date: January 10, 1985
To: CVD Reactor Group
From: Stanley Middleman, Director
Re: Mass Transfer in a CVD Reactor

Chemical Vapor Deposition (CVD) is a heterogeneous reaction process by which various chemical species may be deposited as very thin films on silicon wafers. In the manufacture of semiconductor materials, CVD reactors provide a means of contact of a gas mixture with a set of wafers. One problem in design of such reactors lies in the fact that mass transfer may affect the deposition rate, and that the rate of mass transfer may not be spatially uniform in a CVD reactor.

You are to design an experimental system with which you can explore factors that affect the rate and degree of uniformity of mass transfer in a CVD reactor.

Beginning January 17, and each week thereafter, I expect to receive a typed progress report. We shall also have a weekly meeting at which time your group will make a twelve minute oral presentation to the class on progress and plans for future work. A final presentation is to be given during the week of March 13 and a final report is to be in my hands on March 19.

Please do not hesitate to contact me if you need any technical or administrative help in facilitating your progress.

FIGURE 1. Problem statement to CVD lab group.

Strong emphasis is given to oral and written communication skills. Each week the group meets with the project head to discuss the project and present a written progress report. Project goals may be modified if justified by preliminary experimental results or other extenuating circumstances. The group also has to give weekly oral presentations to the entire class.

COURSE ORGANIZATION

Students work in groups of three or four. After receiving their problem statement, they have two weeks to research the problem area, check out the available resources, consult with the project head, specify the goal and postulate the strategy to solve the problem. The project head mainly serves to provide insights as to whether the proposed project is feasible, trivial, or too ambitious for a ten-week period.

The next four weeks are spent either in con-
struction of new equipment or in modification of an existing apparatus, in performing preliminary experiments and in making further equipment modifications as required. Students are required to submit a mock purchase order for supplies and a job order requesting the assistance of the technical staff in building equipment. To avoid time lag, the lab has to stockpile common items such as rotameters, glassware, valves and fittings. Preliminary experiments usually entail equipment calibration, determination of necessary thermodynamic and physical properties data, solution preparation, and at least several trial runs of the experiment. The main purpose of these preliminary experiments is to allow the students to become familiar and comfortable with the new equipment and to develop clean and efficient techniques. In the process they also learn the importance of careful planning of experiments and the validity of Murphy’s Law in experimental research.

The remainder of the ten-week quarter is used to perform final experiments, analyze data, and prepare final oral and written reports.

During the course of the quarter, the groups are required to submit a weekly progress report (five to eight pages). The grading of the report is broken down into technical content and style. Extremely strong emphasis is given to proper writing style at the beginning of the first quarter. As the writing improves, the grading emphasis moves more toward technical content, much like a refereed journal article might be critiqued. The group leader, who rotates every week, has to edit the report and do the rewriting if requested. Because report revisions are often requested, word processing of the reports is encouraged, using the CATT system on VAX or WordStar on the IBM PC. Over two quarters and including the final reports, each student should have participated in writing sixteen reports.

For the weekly oral report, students are required to give a twelve- to fifteen-minute presentation in which the use of visual aids (either transparencies or slides) is mandatory. The presentations are critiqued immediately after each session by the instructor for the benefit of all. Evaluation forms (Fig. 2) from classmates are passed on to the speaker after the instructor has reviewed them. Students sometimes find that the harshest comments come from their peers.

We schedule two separate oral presentation sections per week, each under the supervision of one of the instructors assigned to the laboratory. Lab groups are rotated in a staggered fashion through these sessions over the quarter. Thus each student faces a different audience for each talk. Moreover, the entire class is exposed to all the different experiments being conducted in the lab.

### LIST OF EXPERIMENTAL PROJECTS

We have listed in Table 1 the experimental projects that were carried out during the 1984-85 academic year (2 quarters; 20 weeks). The objectives listed are a synopsis of the general problem statement which was presented to each lab group at the start of the project.

Several of these experiments are interrelated and provide an opportunity for productive communication between groups. The gas-lift reactor experiment permits examination of gas-liquid
mass transfer in a reactor uniquely designed for the algae growth experiment. The effects of sparger design, bubble size, gas flow rate, and solution electrolyte content on oxygen mass transfer are examined, with special attention given to their role in algae growth.

The aerated stirred-tank experiment keys on mixing and oxygen mass transfer problems in microbial exopolysaccharide production, which is of interest to a local company (Kelco). Through pre-arrangement on the part of the instructors, specific members of the technical staff of Kelco are available to meet with students and provide consultation.

In the gas absorption experiment, in-line static mixers are used to study carbon dioxide absorption into a dilute sodium hydroxide solution in a cocurrent pipe flow configuration, as might be applied to an industrial “gas sweetening” pretreatment process. The system was donated by Komax, which is interested in obtaining performance data for its Komax Mixers in this type of application.

Engineers at Chevron Oil Field Research (COFR) in nearby LaHabra first stimulated our interest in the use of dilute polymer solutions in enhanced oil recovery. Using information they provided, the students were able to set up an experimental study of the effects of polymer configuration in dilute solution on the removal of oil from packed beds. Cylindrical and two-dimensional planar beds with various bead and sand packings have been used. Typical oil recovery polymers, supplied by Kelco and Dow Chemical Co., have been used in both pure water and brine solutions. A variety of experiments have been conducted over the past several years, ranging from single “oil blob” movement in a bed with a monolayer of uniform glass bead packing, to bulk oil displacement from a cylindrical sand packed bed. Parameters of interest are polymer concentration necessary for oil displacement, polymer degradation and adsorption in the packed beds, and the effect of salts on these results.

The chemical vapor deposition (CVD) experiment required the design of a model of an industrial CVD reactor for the purpose of studying mass transfer effects on the vapor deposition process. The development of this experiment was greatly influenced by contacts with researchers in

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<th>TABLE 1</th>
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<tr>
<td>Experimental Projects in 1983-84</td>
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**PROJECT**

1. **Mass Transfer in CVD:**
   To study the role of mass transfer in chemical vapor deposition processes.

2. **Enhanced Oil Recovery/Porous Media Flow:**
   To study efficiency of polymers in enhanced oil recovery. To look into effects of rheology, polymer degradation and adsorption. Flow visualization of oil “blob” movement in porous bed.

3. **Mass Transfer in gas-lift Reactor:**
   The analysis of oxygen mass transfer in fermentation systems. Effect of electrolytes and fluid properties on bubble dynamics. Reactor and sparger design.

4. **Aerated Stirred Tank Mixing:**
   The study of mixing and gas-liquid mass transfer in an aerated stirred tank with non-Newtonian fluids. The application of novel impeller geometries.

5. **Gas Absorption:**
   To obtain design data for a cocurrent pipe flow gas absorber using in-line static mixers.

6. **Heterogeneous Catalytic Reactor:**
   Kinetics of heterogeneous catalytic reactions. To assess mass and heat transfer effects in catalytic CO oxidation and methanation reactors.

7. **High Fructose Syrup Production:**
   The study of immobilized enzyme kinetics, enzymatic reactor design, and ion-exchange column operation in the production of high fructose corn syrup.

8. **Mixing in Chemical Reactors:**
   To study the effect of non-ideal mixing in the performance of tubular and stirred-tank reactors.

9. **Ethanol Fermentation:**
   Ethanol production in batch and continuous fermentation. Fermentation kinetics and bioreactor design.

10. **Algae Growth:**
    The use of algae in biomass production. Effect of mass transport and bubble dynamics on the kinetics of algae growth.

11. **Hollow Fiber Membrane Separation:**
    To study the design problems of hollow fiber separation of biomass in application to microbial systems.

12. **Distillation:**
    Batch and continuous azeotropic distillation problems with an isopropanol/water mixture.

13. **Liquid-Liquid Extraction:**
    The mass transport phenomena and design of a liquid-liquid extraction column with soybean oil as the organic phase.

14. **Plate Heat Exchanger:**
    To design, construct and operate a plate heat exchanger system for use with viscous gelatin solutions.

15. **Wetted Wall Column:**
    Study of gas-liquid mass transfer in falling films of viscous fluids and in the presence of surface-active agents.
the local semiconductor industry who were drawn to UCSD, in part, through the spring quarter Chemical Engineering Seminar Series, which was developed with the theme “Applications of Chemical Engineering in Semiconductor Technology.” An experimental system was built in which naphthalene in a nitrogen carrier gas was deposited on the surface of an acrylic disc. The elimination of chemical reaction from the process served to isolate the mass transfer phenomena.

In the catalytic reactor set-up we have provisions for either CO oxidation or methanation reactions in either packed-bed, recycle, or single-pellet reactor configurations. All recording equipment, including thermocouples and the gas chromatograph, are interfaced to an IBM PC. A BET apparatus is also available for surface area and chemisorption experiments. The combination of all these options allows for a variety of interesting experiments for the students to plan and design.

A biochemical application of the principles of kinetics and reactor design is investigated in the high fructose corn syrup production experiment. This experiment was implemented with the help of information supplied by Staley Co., using immobilized enzymes and ion-exchange resins donated by Novo and Dow Chemical Co., respectively. The goal of the project is to look at more rational reactor and process design procedures. Computer modeling of the reaction/deactivation kinetics is also included.

Classical chemical engineering kinetics and reactor design experiments are conducted by studying mixing in stirred-tanks and tubular reactors. Mixing, as well as mixing with chemical reaction, has been studied in any number of reactor geometries—batch, stirred-tanks in series, tubular flow with static mixers or packed-beds, and any combination of these. Residence time distributions are studied with colored dye tracer and a spectrophotometer with a flow-through cell.

Along with some of the previously mentioned experiments which have a biochemical twist to them, we have a series of experiments which are more directly oriented towards biochemical engineering. Ethanol production is carried out by fermentation using both single and multiple substrate growth media. The extensive cell growth, substrate utilization, and ethanol production data are compared to data generated using classical biochemical kinetic rate models in computer simulations.

The algae growth experiment was initiated due to the interest of a group of scientists at Scripps Institute of Oceanography. They have studied the optimum biological growth conditions (i.e., pH, light, growth medium, and temperature), while our engineering students concentrated their efforts on the role of mass transport in algae growth. As mentioned previously, we have designed a two-dimensional, gas-lift reactor in which both algae growth and mass transfer experiments are conducted. The two-dimensional geometry is useful for flow visualization experiments to determine bubble dynamics and mixing in the reactor. The goal is the optimization of algae growth with respect to mass transfer limitations, while keeping biological parameters constant.

We have used hollow fiber modules donated by Asahi Medical Co. to conduct simple membrane separation experiments. The goal is to examine a process technology for concentrating cell mass in either cell recycle or biomass production processes.

We do have some conventional chemical engineering unit operations experiments in the lab. In the distillation experiment, the students have had to design their own plumbing and control schemes to convert a three inch diameter, six stage batch bubble cap column to continuous operation. The column feed is a cleaning solution provided by the university glassblower (a 35/65% isopropanol/water mixture with some minor impurities). Extractive distillation techniques (e.g. the addition of a salt into the column) has been applied to produce an isopropanol/water distillate of 85-90% purity. The students must also generate their own thermodynamic data. A gas chromatograph is used for data analysis and computer simulations of the distillation column are also conducted.

The liquid-liquid extraction experiment uses soybean oil as the organic phase, mainly due to cost and safety reasons, but also because of the novelty of the process. The operation of the column for such a viscous continuous phase is quite different from conventional extraction processes. The students must design experiments to examine transport phenomena in the column (e.g. droplet coalescence and break-up) and they must determine solubility data before they can design and conduct the extraction experiment.
The plate heat exchanger experiment was initiated and financed through a contract received from Eastman Kodak Co. The interest of Kodak is in the use of a plate heat exchanger to heat and cool photographic gelatin solutions. The students must design and construct the experimental apparatus and then obtain the heat transfer and design data required by Kodak. The experimental and logistical novelty of this project is that the process fluid is a gelatin solution and the students act as if in a consulting capacity to a contracting employer. This program will continue over several quarters and will require that students study the reports of preceding groups, building upon their progress.

The wetted-wall column is a standard counter-current gas/liquid contacting device. The students are able to change tube dimensions and gas and liquid Reynolds numbers to examine mass transfer coefficients in different flow regimes. Water/air mass transfer data are compared to classical correlations. The use of the column with surface active agents and to concentrate viscous aqueous solutions has also been investigated.

DISCUSSION

Since our students only work on one project each quarter (compared with the more standard rotation of four to six experiments), it appears that we are sacrificing breadth of exposure to different processes for in-depth studies of two topics. However, a single project quite often involves learning how to use several equipment items or performing experiments (such as generation of fluid property data) which are frequently used as separate experiments in rotation-type lab courses. In addition, students can learn from the oral presentations and laboratory interactions with classmates. It has been our experience that the present system stimulates inter-group interaction. Feedback from our graduates reinforces our opinion that the uniqueness of the present experience far outweighs it drawbacks.

The two major constraints on the lab are those that are common to many industrial and academic projects: time and money. Experimental set-ups are taken apart every year and, not infrequently, even after each quarter. New experiments are frequently introduced and old experiments are rotated in and out depending on student interest. In the second quarter the students are allowed to select new experiments of particular interest to them from among those we have the facilities to implement. As for old experiments, objectives often are changed for a new lab group in the second quarter, and may be different enough that modifications of the apparatus are required. To this end, we strike a cautious compromise between our available resources and our creative urges.

Over the years we have also noticed a certain latency period in the first quarter of the lab. It usually takes the students several weeks to adjust from the cookbook-trained mentality to the point where they gain the confidence to rely on themselves. In several isolated cases we also have to deal with individuals who are over-enthusiastic and put unreasonable demands on the technical staff. Gradually, they all learn to deal with independence, bureaucracy, lab techs, and fellow group members who may not have the same motivation or philosophy.

Group dynamics are more obvious in the present environment, since the lab group has to go through so many oral and written reports in addition to interactions with the project head. Students with leadership qualities, characters with nonchalent attitudes, “gofers,” and any possible strains within a group are quite observable.

CONCLUSION

We feel that we are successful in developing the oral and written communication skills of our students, while providing a forum for innovative thought. We also have a lab which allows our students to get acquainted with new industrial developments, such as microelectronic fabrication and biotechnology, and with the integration of new technology, such as microcomputer applications, into laboratory experiments.

The progress in oral communication skills is particularly significant and rewarding. We feel it is a direct result of the fact that each student has to give a minimum of six talks. (There are additional opportunities for oral presentations in the computer-aided design and process design courses.) The emphasis is on the student making a very professional presentation. We have received quite a number of comments from industrial employers commending us on the speaking abilities of our graduates.

The improvement of the writing skills is a little harder to gauge, even though the students show obvious progress through the two quarters. As anyone who has taught a writing class knows, students have a notoriously high rate of reversion

Continued on page 161.
THIS COURSE TEACHES the fundamental scientific principles controlling most chemical, petrochemical, and refining processes. The student population consists mainly of junior and senior chemical engineers, but the information is of equal value to advanced chemistry majors. A few mechanical engineers interested in plant construction also take the course. The objective of the course is to provide the student with a fundamental understanding of the chemical, catalytic and engineering sciences relating to the chemical reactions taking place in a variety of reactors of different configurations. Although many major commercial processes are discussed in the course, the emphasis is not on an enumeration of all of the major processes, but the direction is placed on understanding how and why the chemical transformations occur. This science is then merged with the technology of the two dozen or so reactors of radically different designs and configurations currently used commercially. Thus, the student gains an understanding not only of the process fundamentals but also of the devices used to successfully perform the processes. The course is kept current each year by introducing new processes which are in commercial development. Synthesis gas generation and utilization are discussed to address a long range technological need of engineering and science students. For the chemical engineering students the course serves the specific function of allowing them to become more conversant with chemical phenomenon. This is purposely done in response to the criticism from both industrial and academic scientists who feel that the current U.S. training of chemical engineers is deficient in chemistry. This course has a chemical orientation but it is placed in the context of learning all of the fundamental sciences which govern the major commercial processes which they will deal with in the future. The student should gain enough fundamental understanding of the chemical phenomena occurring inside of reactors of different designs so that in their future work they will be able to execute superior process designs and controls for these or other new processes.

COURSE DESCRIPTION

The prior requirements for the course are a fundamental organic chemistry course, an introductory inorganic chemistry course (usually included in the freshman chemistry series), and a keen interest in chemical engineering and chemical processes. Since the course is descriptive and qualitative, prior chemical engineering courses involving quantitative engineering calculations are not required.

A successful presentation of the technology described by this course requires the application of several principles of chemical engineering, organic, inorganic and physical chemistry, thermodynamics, kinetics and mechanical engineering. Thus, the instructor must make a careful choice as to the degree of review of these subjects which is adequate for the understanding of the chemical process technology. The approach currently used at WPI is to provide a concise review of just those principles which are required to master the chemi-
The technology presented in the course is accomplished in 24 lectures of 50 minute duration. In addition to outside reading from a list of 89 references taken from the original technical literature, three term papers are required on topics which are not discussed in the classroom lectures. Three one-hour, closed note and closed book exams are usually given during the duration of the course. The textbook currently used for the course is *Chemistry of Catalytic Processes* by Gates, Katzer and Schuit (McGraw Hill, 1979).

The course is divided into the following eight major topics:

1. Survey of Major Chemical and Refining Processes
2. Homogeneous Catalytic Process Fundamentals
3. Heterogeneous Catalytic Process Fundamentals
4. Survey of Modern Commercial Reactor Configurations
5. Synthesis Gas Generation
7. Technology of Major Advanced Chemical Processes
8. Major Refining Processes

The division of lecture time committed to each topic may be seen in Table 1. The timing of exams and due dates for term papers is also shown. A

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**TABLE 1**

Chemical Technology: Course Schedule

<table>
<thead>
<tr>
<th>Lecture Number</th>
<th>Subject</th>
<th>Lecture Number</th>
<th>Subject</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Survey Major Chemical Processes</td>
<td>13</td>
<td>Reactor Configurations for Major Processes</td>
</tr>
<tr>
<td>2</td>
<td>Homogeneous Metal Catalysis</td>
<td>14</td>
<td>Synthesis Gas Catalysis and Synthetic Fuels</td>
</tr>
<tr>
<td></td>
<td>(A) Major Processes</td>
<td>15</td>
<td>Synthesis Gas Production Processes (A) Reforming</td>
</tr>
<tr>
<td>3</td>
<td>Homogeneous Metal Catalysis</td>
<td>16</td>
<td>Synthesis Gas Production Processes (B) Gasification (C) Downstream Processing</td>
</tr>
<tr>
<td></td>
<td>(B) Co-ordination Chemistry</td>
<td></td>
<td>Synthesis Gas for Chemicals and Fuels (A) Methanol Synthesis Problem Set #2 Due—Catalytic Cracking</td>
</tr>
<tr>
<td></td>
<td>(C) Bonding</td>
<td>17</td>
<td>Synthesis Gas for Chemicals and Fuels (B) Methanol to Aromatic Gasoline (C) ZSM-5 Catalysis</td>
</tr>
<tr>
<td></td>
<td>(D) Reactivity</td>
<td>18</td>
<td>Synthesis Gas for Chemicals and Fuels (D) Fischer-Tropsch Catalysis</td>
</tr>
<tr>
<td>4</td>
<td>Homogeneous Metal Catalysis</td>
<td>19</td>
<td>Synthesis Gas for Chemicals and Fuels (E) New Syngas Processes for Ethanol, Vinyl acetate, and acetic anhydride Problem Set #3 Due—Heterogeneous Partial Oxidation</td>
</tr>
<tr>
<td></td>
<td>(E) Metals</td>
<td></td>
<td>Synthesis Gas for Chemicals and Fuels (F) New Syngas Processes for Ethylene Glycol, Styrene, Xylenes</td>
</tr>
<tr>
<td></td>
<td>(F) Stereochemistry</td>
<td>20</td>
<td>Synthesis Gas for Chemical Intermediates (A) Acetic Acid</td>
</tr>
<tr>
<td></td>
<td>(G) Key Intermediates</td>
<td></td>
<td>EXAM—SYNTHESIS GAS TECHNOLOGY (B) Fischer-Tropsch Catalysis</td>
</tr>
<tr>
<td>5</td>
<td>Homogeneous Metal Catalysis</td>
<td>21</td>
<td>Synthesis Gas for Chemicals and Fuels (F) New Syngas Processes for Ethylene Glycol, Styrene, Xylenes</td>
</tr>
<tr>
<td></td>
<td>(H) Key Transformations</td>
<td></td>
<td>Advanced Technology for Chemical Intermediates (A) Acetic Acid</td>
</tr>
<tr>
<td>6</td>
<td>Homogeneous Metal Catalysis</td>
<td>22</td>
<td>EXAM—SYNTHESIS GAS TECHNOLOGY (B) Fischer-Tropsch Catalysis</td>
</tr>
<tr>
<td></td>
<td>(I) Ligand Effects on Reactivity</td>
<td></td>
<td>Mature Technology for Chemicals (A) Wacker Process (B) Butane Oxidation (C) Hydroformylation</td>
</tr>
<tr>
<td></td>
<td>(J) Classification of Reactions</td>
<td></td>
<td>Refining Processes (A) Hydrodesulfurization (B) Reforming</td>
</tr>
<tr>
<td>7</td>
<td>Heterogeneous Catalysis</td>
<td>23</td>
<td></td>
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<tr>
<td></td>
<td>(A) Major Processes</td>
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<tr>
<td>8</td>
<td>Heterogeneous Catalysis</td>
<td>24</td>
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<tr>
<td></td>
<td>(B) Surface Adsorption</td>
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<td></td>
<td>(C) Surface Kinetics</td>
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<td>9</td>
<td>Heterogeneous Catalysis</td>
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<td></td>
<td>(D) Surface Chemistry</td>
<td></td>
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<td></td>
<td>Problem Set #1 Due—Ziegler-Natta Catalysis</td>
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<td>10</td>
<td>Heterogeneous Catalysis</td>
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<tr>
<td></td>
<td>(E) Types of Catalysts</td>
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<td>11</td>
<td>Heterogeneous Catalysis</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>(F) Zeolites and Their Structures</td>
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<tr>
<td>12</td>
<td>Heterogeneous Catalysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(G) Zeolites and Their Catalysis</td>
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SUMMER 1985
brief description of the topics treated in the lectures for the eight major areas listed above follows.

1. Survey of Major Chemical and Refining Processes

The topic is introduced with a definition of the four principal types of reactions utilized in commercial reactors, e.g., heterogeneous catalyzed, homogeneous catalyzed, gas phase catalytic and non-catalytic, stoichiometric reactions in solution with their individual variations. Examples are given for each class. Also terms like conversion, selectivity, yield, etc., are defined.

2. Homogeneous Catalytic Process Fundamentals

Examples are given of the top fifteen commercial processes using homogeneous catalysts. The student would be expected to know the reactants, products, catalysts, and approximate reaction conditions for each process. Several new processes which are currently being considered for commercialization are also listed.

This section includes the important fundamental information on homogeneous catalysis. Thus, the key coordination chemistry principles required to understand the homogeneous catalyzed process (to be described later on) are tightly reviewed and discussed. A few of the concepts discussed are: elements of crystal field-molecular orbital theory; metal d-orbitals; d-electron activation of coordinated ligands; coordination stereo-chemistries of transition metal complexes; counting d-electrons; eighteen electron rule; key intermediates in homogeneous catalysis like metal carbonyls, hydrides, alkyls, etc.; key transformations in homogeneous catalysis like oxidative addition, insertion, electron transfer, etc.; ligand electronic and steric effects such as pi-acceptors, sigma-donors, cone angles, etc. Then the basic sub-classification of homogeneous metal catalyzed reactions like main group and transition metal catalysis, biocatalysis, phase transfer catalysis, polymer supported catalysis, etc., are briefly described. The typical kinetic treatments and methods for spectroscopic analysis are also illustrated.

3. Heterogeneous Catalytic Process Fundamentals

Fifteen examples are given of major commercial processes in terms of reactants, products, catalysts, and conditions, along with a brief discussion of a dozen other processes.

The fundamental aspects of heterogeneous catalyzed processes are discussed by reviewing principles of the chemistry and physics of surfaces and surface adsorption, e.g., macro- and micro-pores, Knudsen diffusion, chemisorption and physical adsorption; Langmuir-Hinshelwood and Rideal-Eley surfaces kinetic models, competitive chemisorption and catalyst poisoning; surface intermediates and surface chemistry.

This section also discusses the major sub-categories of heterogeneous catalysts like supported and unsupported reduced metals, solid state inorganic catalysts, carbon catalysts, clays and zeolite catalysts. Several examples are given for each class.

A detailed discussion is devoted to the structure, physical and chemical properties, and catalytic properties of zeolites. Some of the topics discussed are X- and Y-type zeolites and ZSM-5 structures, modifications and molecular build up; pore openings and crystal structure; super acidity and super basicity; and a four component model for rationalizing the unusual activity of zeolite catalysts. The student is also introduced at this point to the relationship of shape selectivity and constraint index to the crystal and catalytic properties of zeolites. An assortment of several classes of zeolite structures is illustrated with 35 mm slides and three dimensional molecular models. Support materials used in heterogeneous catalyzed processes and their criteria for selection are briefly discussed.

4. Survey of Modern Commercial Reactor Configurations

Drawings of fourteen of the reactor configurations used commercially in both heterogeneous and homogeneous catalyzed processes are supplied to the student, and an example is given of a commercial product produced using each configuration. Within the discussion of these reactor configurations, the various thermodynamic, heat transfer, kinetic, reactor stability, mixing and other factors giving rise to the selection of a specific configuration, are examined. Specific examples of reactor configurations (process applications) are as follows: tube and shell (Lurgi methanol and ethylene oxide process); tray re-
actor with interstage cooling (ICI methanol synthesis); riser tube (catalytic cracking); fluidized bed (SOHIO acrylonitrile); slurry tank (polypropylene); radial bed (styrene synthesis); and others.

5. Synthesis Gas Generation

The major processes used in the production of synthesis gas are discussed along with their feedstocks and gaseous product compositions. The thermochemistry of each process is related to thermal and pressure effects on the syngas product ratios and to its consequence on the reactor design. Drawings for several process reactors such as methane reforming, partial oxidation, Lurgi non-slacking gasifier, Koppers-Totzek gasifiers and the Bi-Gas slugging gasifier are provided to the student along with a discussion of each. A survey of next generation gasifiers is given.

Post gasifier processing of raw syngas through water gas shift, bulk and trace sulfur removal processes, CO₂ removal and CO separation from H₂ is discussed. The chemistry of a Claus plant and Stretford plant is summarized.


A survey of all commercial and potential fuels and chemicals processes using a syngas feedstock is given with reactants, products, catalysts, and reaction conditions. Details of the thermochemistry of methanol synthesis and its consequence on the evolution of the ICI, Lurgi and Chem Systems reactor and process configurations are discussed. The student is introduced to conventions used in process stream notations. The low pressure catalyst structure and syngas to methanol surface reaction mechanism are presented.

A detailed discussion is given to the conversion of methanol by the Mobil M process to aromatic fuels. The details of the ZSM-5 catalyst structure,
acidity, and shape selectivity are merged with a detailed evaluation of an intercrystalline surface mechanism to understand the product distribution and catalyst stability.

A thorough discussion is devoted to the ARGE fixed bed and fluidized bed SASOL processes for the direct conversion of syngas to fuels. Catalysts, reactor configurations, slides of the Sasol II Plant, surface reaction mechanistic models, Schulz-Flory kinetics and thermochemistry of syngas conversion to various products are parts of these lectures.

The lectures on the conversion of synthesis gas to chemicals is less oriented toward reactors and total processes; rather, they concentrate more on the detailed reaction mechanisms, using the pertinent coordination chemistry intermediates, to rationalize the conversion of syngas to various products. This is the first opportunity that the student has in the course to apply the fundamentals learned earlier to homogeneous and heterogeneous catalyzed processes. Some of the processes discussed are: acetic anhydride, acetic acid, ethylene glycol, vinyl acetate, and ethanol.

7. Technology of Major Advanced Chemical Processes

This section also concentrates on reaction mechanisms for both homogeneous and heterogeneous catalyzed processes. Aromatic side chain oxidation and butane oxidation to acetic acid are described by listing each of the proposed individual, elementary reactions required to form products. The coordination chemistry of the Wacker process, Carbide and Shell oxo-processes, Halcon propylene oxide process and others are illustrated. Likewise, the proposed surface mechanisms for the super basic zeolite catalyzed conversion of toluene and methanol to styrene and ZSM-5 zeolite catalysts for p-xylene production are explored along with several other.

8. Major Refining Processes

The principal processes utilized in a modern refinery are surveyed. A few of the processes like hydrotreatment are described in detail by way of an examination of the crystal chemistry of the catalyst, processing of various feedstocks, and reactor configuration. Most of the students’ understanding of catalytic reforming, and catalytic cracking comes from assigned textbook reading. Several of the processes are viewed by 35 mm slides of various refinery units.

TERM PAPERS

Three term papers are assigned for the purpose of examining the details of several important areas of chemical and petroleum processing technology which are not covered in class. The emphasis in the papers is to provide a concise description of the major scientific and engineering aspects of the technology. In the past, Ziegler-Natta catalysis, catalytic cracking, and technology of heterogeneous, hydrocarbon partial oxidation were assigned.

EXAMS

Three one-hour exams are usually given which cover all material discussed in class. These exams are closed notes and books and are given soon after the subject matter is discussed in class. No comprehensive final has been given until now. Table 2 shows a typical exam, given in March of 1982. The high grade was 99, the low was 41, and the class average of 53 students was 70.

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Continued from page 127.

thanks go to Colin Pritchard, Norman Macleod, Mike Davidson, Jack Ponton, Don Glass, Leong Yeow and Jeff Lewis.

REFERENCES

LETTER TO THE EDITOR
Continued from page 135.

Another important refinement is to modify the impeller in the “mixer” which is a small centrifugal pump that blends together the reactant streams entering the reactor tube. In our particular reactor geometry, the impeller of the pump sent rapid pressure pulses back to the dye rotameter causing violent fluctuations of the bead in the dye rotameter. Our solution was to replace the impeller blade with a flat disc. The rotation of the disc generates sufficient shear to blend the streams.

R. R. Hudgins
University of Waterloo

PACKAGED SOFTWARE
Continued from page 147.

these packages. To this end an increased student awareness and familiarity with these facilities can only be beneficial.

ACKNOWLEDGMENTS

The author wishes to acknowledge assistance and co-operation from the following members of staff: A. M. Gerrard, J. Notman (Department of Chemical Engineering), P. R. Bunn (Department of Electrical, Instrumentation and Control Engineering), and research students J. C. Cheow, S. Acey, and C. K. Goh.

REFERENCES


PROCESS LAB
Continued from page 155.

to bad habits as soon as they stop writing regularly.

The feedback from the students has been extremely positive. They fully enjoy the opportunity to work on what they regard as their own problems. We have not come across a course which puts so much demand on the students but receives so few complaints. (The actual lab work extends well over the regular six hours per week scheduled in addition to the time required for report writing and preparing oral reports.)

The support from industry has also been encouraging. We continually receive financial aid and equipment donations as well as new ideas for experiments. In the next year we expect to receive an industrial scale CVD reactor, a spin coating apparatus and an experiment to perform membrane separation of gasses. Our lab course would not have been so successful without this continued support.

ACKNOWLEDGMENTS

We would like to thank our industrial supporters—Chevron, Kelco, Eastman Kodak, and Komax—for their donations of equipment, materials, information, and money. Finally, we are indebted to the AMES department technical support staff—Joe Robison, Paul Engstrom, Ray Hummer, and Jon Haugdahl—for their continued help and understanding (both with students and instructors!).

REVIEW: Cost Engineering
Continued from page 119.

other new topics added to the first edition such as an analysis of overtime costs, information on rework costs, and the handling of back charges. These topics are illustrated by actual industrial examples. Additional new information on bulk material control, monitoring construction field labor overhead, labor productivity, and forecasting direct labor are illustrated with other industrial examples. The chapter on contingency estimating and its application to cost control has been rewritten to reflect recent developments. The treatment of estimate types and accuracies likewise has been updated. Because of the omnipresent computer, an introduction to computerized estimating has been added since the first edition. Advice is provided on how to go about computerizing routine estimating tasks.

This edition is the first book in a planned series of about 20 which concern cost engineering and related topics. Of the twenty, six have already been published. This series will cover the whole gamut of cost engineering topics for the student and for the practicing cost engineer.
ADJUNCT POSITION
One Way to Keep Up With Technology and Education

RICHARD D. NOBLE
University of Colorado
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A great dilemma in engineering education is how an individual can become an excellent teacher and also keep up with the latest technical developments in his field. This is especially difficult during this present period of rapid technological advance in many fields, such as computers, and the emergence of new fields, such as biotechnology.

What are some of the problems associated with an academic professional keeping up in both technology and education? An instructor normally has had little or no formal training in educational skills. Also, at many schools there is a lack of emphasis and a lack of rewards for good teaching. This makes it difficult for an individual to develop the necessary skills to be a good teacher. In technical research, the emphasis at many universities is to obtain contract research. This in itself is a difficult task. Once the funding is obtained, it may be very difficult to perform good work due to a lack of graduate students, poor laboratory and/or computer facilities, or an inadequate library.

There are many possible avenues to solving this problem. Sabbaticals, leaves of absence, consulting, and graduate research are all possible means for keeping up with technical advances, while attending educational meetings and seminars can help to improve teaching skills. This paper describes an approach that the author has used to keep up with both technology and education: combining technical work at a national laboratory with an adjunct faculty position at a university.

At a time when there are still many unfilled faculty positions, this approach provides one method to deal with the problem. Some faculty may view an adjunct position as a temporary (one- to three-year) method to develop research skills while still “keeping up” educationally.

THE POSITION AND BENEFIT

I currently have a position as a chemical engineer doing research in mass transfer separations at a national laboratory. My job description also allows me to teach one course per semester as an adjunct faculty member. I teach one graduate course and one undergraduate course in transport phenomena (the same subject area as my technical work). The laboratory allows me time to perform my teaching duties and to attend educational meetings such as the ASEE annual meeting. The chemical engineering department pays my travel expenses to these educational meetings in lieu of salary. An outline of some benefits is shown in Table 1.

TABLE 1
Some Benefits of An Adjunct Position

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<th>STUDENTS</th>
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<td>- Develop teaching skills</td>
<td>- Employee morale</td>
<td>- Inexpensive labor</td>
<td>- Exposure to modern technology</td>
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<td>- Conduct technical research</td>
<td>- Public relations</td>
<td>- Additional faculty</td>
<td>- Work with modern facilities</td>
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<td>- Modern facilities</td>
<td>- Highly skilled employee</td>
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<td>- Interaction with students</td>
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<td>- Publications</td>
<td>- Public relations</td>
<td>- Public relations</td>
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<tr>
<td>- 12 month salary</td>
<td>- Added technical skills</td>
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What are the benefits to me? I can continue to use and improve my teaching skills by continued teaching and by attendance at educational meetings. I keep up with the material in the area of transport phenomena by continued teaching and technical research, and I keep up with the technical advances in my field by conducting research and attending technical meetings. I can use up-to-date facilities to conduct research. I get to interact with both undergraduate and graduate students and work with them on research projects. Continued educational and technical work allows me to publish in educational and technical journals. I also have a 12-month salary, so I do not have to develop additional summer support for myself.

What are the benefits to my employer? First, they have a happy employee. If I am enjoying my job, they benefit. They also get the public relations benefit of demonstrating their support for higher education by having an adjunct faculty on their staff. They have an employee who is technically “up” in his field through continued teaching in his subject area, and they enjoy the benefits of “cross-fertilization” through interaction with university colleagues. The employee also develops communication skills through teaching. Students work at the laboratory for a small salary or for credit (no salary), so the labor force is inexpensive and usually productive. Some of the students may decide to work for the employer upon graduation because of their work experience, so there is also a recruitment aspect for the employer.

What are the benefits to the university? They get “cheap” labor in a time of fiscal restraints and they get a faculty member in a time of faculty shortages. They get the public relations benefit of having teachers who have up-to-date technical knowledge, and they also get additional technical skills in their department.

Last, but not least, what are the benefits to the student? Students are exposed to modern technology as it is introduced in the classroom by the adjunct instructor. They have an instructor who is “up-to-date” and who can translate the concepts learned in class to new developments in technology. For students who work with the adjunct professor, there are added benefits. They get to use modern “state-of-the-art” equipment, and through their work they can gain experience in certain jobs and determine if they wish to pursue them after graduation. For graduate students, working with modern facilities can make their work more productive since they spend less time reducing data and maintaining equipment.

There can also be negative aspects to this type of arrangement. Adjunct faculty have little or no time to meet with students outside of class. If the adjunct has had limited training in teaching, the communication of information between faculty and students can be impaired. A job such as I have described requires the full and continuing support of both the employer and the university. If that support is lacking, it would be very difficult to do a good job.

CONCLUSION

Combining technical training with an adjunct faculty position has been shown to be an effective mechanism for maintaining technical and educational skills. Benefits to the individual, the employer, the university, and the student are varied and important. The particulars of an adjunct position are often flexible and depend on the interests and objectives of the parties involved.

ACKNOWLEDGMENT

This paper was originally presented at the ASEE Gulf Southwest Regional Conference, University of Houston, March 13, 1982. A revised version was presented at the ASEE Summer School for Chemical Engineering Faculty, University of California, Santa Barbara August 1-6, 1982. I am indebted to the many individuals who have provided comments during these presentations.
TEACHING PROCESS DESIGN
Continued from page 123.

The cold gas is warmed in the heat exchanger to 65°F and leaves with an enthalpy of 161 Btu/lb. Since the mass flow is the same on both sides of the heat exchanger, the enthalpy decrease of the liquid CO₂ is the same as the enthalpy increase of the cold gas, which is (161-148) or 13 Btu/lb. The enthalpy of the liquid going to the valve (and entering the condenser) is now (65-13) or 52 Btu/lb. So the refrigeration is

$$45,300 \times (148 - 52) = 4,350,000 \text{ Btu/hr}$$

The student recognizes that the high-pressure heat exchanger might be expensive (he suggests that the high pressure liquid would flow through tubes and the 200 psia gas through the shell) and doesn't know if the extra 590,000 Btu/hr of refrigeration would warrant the cost of this additional piece of equipment (he hopes that he will soon get a course which will enable him to answer such questions).

DISCUSSION

The possible ramifications of this sort of development of a thermo problem are enormous. But this is a course in thermodynamics and must move along—there is a lot more subject matter to cover. The problem has been a good workout in the use of a Mollier diagram and in the application of the first law flow equation to heat transfer equipment and to a Joule-Thomson expansion, as well as the calculation of isentropic compression power. The calculations are simple so as not to divert the student from the ideas introduced. Elementary concepts of process design are encountered (possibly for the first time), and the student has an opportunity to invent and compare alternative process schemes. There is a continuous feedback from analysis to better design.

There are many angles which can be developed in the discussion. The book and the course lectures have seemed to suggest that reversible processes are highly desirable. What are the irreversible features of the fourth student's flow sheet? Can they be reduced or eliminated? Can the common work functions ("availability") be used to calculate the operation of a wholly reversible process. Can a completely reversible process be described? Could an expansion engine be employed? Could the heat exchangers be made reversible, even with a zero temperature difference at one end? Is counter-current flow in the exchangers desirable or necessary? What is the origin of the stipulation of a 5°F minimum temperature difference? The second student found the high pressure gas to liquefy partially in passing through the valve. Is this phenomenon peculiar to CO₂? Could the book formulas for the Joule-Thomson coefficient be useful? What experimental procedures were employed to get the data on which the Mollier chart is based? If we had had no chart, could we have made useful calculations? Could we make a similar analysis for the case of a natural gas well (pure methane; or 90% methane, 10% ethane)? Would it be better to use a separate ammonia refrigeration plant, or possibly some combination of ammonia refrigeration plus Joule-Thomson expansion of the gas stream? Where would cooling water come from in New Mexico? What are water cooling towers and how do they work? Why 200 psia in the pipeline? Etc., ad infinitum.

DIFFICULTIES OF THIS APPROACH

The possibility of introducing design thinking into theoretical subjects depends primarily on the interest and competence of the instructor. It can be done, for some M.I.T. instructors have been doing it for years. My department's most successful teacher, Dr. W. K. Lewis, has done this sort of thing all his life. Students in engineering generally like the approach and find that it helps them greatly to understand the theory.

The instructor who worries continually about the things he must "cover" hesitates to "take the time out" for this sort of discussion. Instructors often lack the practical engineering background to do it successfully. Such background (and material for good problems) often comes from high-level engineering consulting work. The rise of engineering science and the increased consulting work by younger staff members may have resulted in most of the staff's consulting being devoted to the more scientific "analysis" kind of activity, rather than to engineering design. It might even be suspected that only about half of the M.I.T. engineering staff are true engineers in the sense of being competent in design, and that the fraction is getting smaller. The most important single thing M.I.T. can do to improve the instruction in engineering design is to engage more instructors who are enthusiastic about the subject and who have not yet become so enamoured of engineering science that they have lost interest in design.
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