CEE

chemical engineering education

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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

BILL CORCORAN of Caltech

LECTURE

Close Encounters of a Sparse Kind
ARTHUR WESTERBERG

PASPEK, VARMA, CARBERRY • Utilization of the Recycle Reactor

HOWARD • The Importance of Teaching

KABEL • The Prairie Dog Problem

WOODS • Using Trouble Shooting Problems

FAHIDY • Co-op Ph.D. Program in Chemical Engineering

also ***WHAT IS*** **CACHE?**

ChE is Running Well at COLORADO UNIVERSITY

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ChE running well at CU! From left to right: Profs. Krantz, Clough, Ramirez, Brown, MacGregor, Falconer, Peters and Timmerhaus.

ChE department

ChE IS RUNNING WELL AT COLORADO UNIVERSITY

WILLIAM B. KRANTZ
University of Colorado
Boulder, Colorado 80309

Of course ChE is running well at CU; or, haven't you noticed which department has won AIChE's Van Antwerpen Trophy for the Four Mile Relay for the past two years? The "running" analogy is an appropriate one for chemical engineering at the University of Colorado. Indeed, because of its unique environment, Boulder, Colorado, has become known as "America's Running Capital." Just as Boulder's environment attracts the top runners in the U.S., it also attracts top students and faculty to its University. Boulder's high altitude provides a superb training environment for world-class runners; analogously, its proximity to major government research laboratories, the nation's richest oil shale deposits and vast coal resources, and to the alpine and arctic climate zones of the Rocky Mountains, provides a stimulating environment for chemical engineering research.

The running analogy can be carried further yet. In running a relay race, each runner must perform to the best of his ability with little direct help from his teammates; yet, it is the team that wins the race. So, too, it is with our Department at CU; each faculty member is contributing to teaching, research, and national service to help our team in the quest for "world-class" excellence in chemical engineering education.

HISTORY OF THE DEPARTMENT

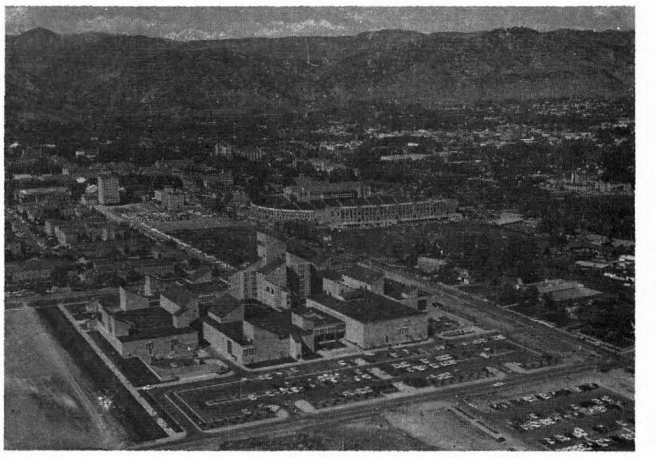
THE UNIVERSITY OF COLORADO opened its doors in September, 1877, one year after Colorado became a state. The School of Applied Science, later to become the College of Engineering and Applied Science, came into being in 1893. This fledgling University was literally a product of its uncommon environment. Its first buildings, as well

as those being added today, are constructed from the pink sandstone quarried along the base of the foothills immediately west of Boulder. This university campus with its red tile roofs has an architectural integrity not found on many U.S. campuses today. The University in its wisdom still preserves and uses its first three major permanent buildings.

The research effort at CU, even in these early days of the University, was heavily focused on energy. Dr. Charles S. Palmer of CU had invented the thermal cracking process for making gasoline from crude oil fractions. Subsequently, the oil testing and coal analysis research conducted in the Mechanical Engineering Department, led to the development, in 1904, of a chemical engineering curriculum as an option in that department. The emergence of the chemical engineering curriculum at CU intensified the research effort in energy-related areas. Early efforts concerned methods of analysis for Colorado coal and efficient technologies for burning lignite. Chemical engineers at CU were also cooperating with the U.S. Bureau of Mines in operating a laboratory to investigate methods for extracting oil from shale.

In 1936 Chemical Engineering became a separate department under Dr. Henry A. Coles. After his resignation in 1938, Dr. Carl W. Borgmann became the department head. Borgmann's dynamic leadership attracted faculty such as Professor George Löf, who is among the pioneers in solar energy research, and Professor Charles H. Prien, whose research concerned the hydrogenation of coal and oil shale. The Department responded to the technical demands of World War II by research centered on the production of activated carbon from soft coal for use in gas masks, the improvement of oil shale processing, and other war-related tasks. Early accomplishments also included the development of a pilot plant which for several years provided the only source of high purity crystalline levulose in the world.

Professor B. E. Lauer assumed the headship in 1947. Under his direction, the Department of Chemical Engineering became, in 1948, the first department in the College of Engineering to offer the Ph.D. degree. Professor Lauer served as editor of four volumes of *Chemical Engineering Laboratory Problems*. These compilations of laboratory experiments, contributed by ChE departments from throughout the world, have helped many ChE departments modernize their undergraduate ChE laboratory courses. Professor Max S. Peters joined the Department in 1962 and



An aerial view of CU looking west showing the Engineering Center in the foreground.

served as Dean of the College of Engineering at CU until his resignation in 1978. In 1963 Klaus Timmerhaus became Associate Dean of the College of Engineering, a position in which he continues to serve.

Professor Barrick temporarily assumed the chairmanship in 1963. He was succeeded in 1964 by Professor R. Curtis Johnson. Under Johnson's leadership the Department began its efforts in computers, controls, and bioengineering, and continued to capitalize on its unique location by expanding its research in environmental engineering. In 1966 Johnson directed the move of our Department into its new facilities within the recently constructed Engineering Center. This magnificent structure, built at a cost of $8.5 million, complements the grandeur of its setting at the foot of the Colorado Rockies. Chemical Engineering

. . . proximity to major government research laboratories, the nation's richest oil shale deposits and vast coal resources, and to the alpine and arctic climate zones of the Rocky Mountains, provides a stimulating environment for chemical engineering research.

occupies 28,200 square feet of laboratory space within the 440,000 square feet of the ten semi-independent structures which comprise the Engineering Center. Courts, fountains, pools, covered walkways, and other amenities within the complex provide an attractive study environment.

Professor W. Fred Ramirez succeeded Johnson as chairman in 1972. Ramirez strengthened our bio-engineering program by bringing Professors R. Igor Gamow and Ronald J. MacGregor into the Department. In addition, he negotiated with CU's Cooperative Institute for Research in Environmental Sciences (CIRES) to create a joint faculty position in Chemical Engineering. In 1976 Professor Robert L. Sani became the first CIRES Fellow in the Department of Chemical Engineering. Professors Ramirez and David E. Clough have been primarily responsible for the implementation of several on-line computer systems in our ChE laboratories. These include a six-computer network of Data General micro-Novas and central Eclipse S/130 minicomputer acquired via a recent NSF Engineering Research Equipment Grant to provide distributed data acquisition and control facilities for our research programs.

After resigning as chairman, Ramirez received one of the first CU Croft Professorships in order to pursue research full-time during 1980. He is succeeded as chairman by Professor Lee F. Brown.

We . . . believe that this blend of teaching quality, research productivity, and professional service commitment is required for world class "excellence" in chemical engineering education.

The present faculty of the Department includes Professors Paul L. Barrick, Lee F. Brown, R. Curtis Johnson, William B. Krantz, Max S. Peters, W. Fred Ramirez, Robert L. Sani, Klaus D. Timmerhaus, and Ronald E. West; Associate Professors R. Igor Gamow and Ronald J. MacGregor; Assistant Professors David E. Clough and John L. Falconer; Professor Adjoint Howard J. M. Hanley; and Professors Emeritus Frank Kreith and B. E. Lauer.

CURRICULA

THE B.S. DEGREE IN CHEMICAL engineering at CU is a four-year program requiring 136 semester credit hours. The 36 hours of required courses in the ChE Department include computing, engineering materials, stoichiometry, fluid flow and heat transfer, mass transfer operations, thermodynamics, engineering statistics, unit operations laboratory, process dynamics, kinetics, and process synthesis and design. The curriculum requires 26 hours of chemistry, 15 hours of mathematics, nine hours of physics, and a minimum of 24 hours of social-humanistic electives and 19 hours of technical electives. Bioengineering-premedical, environmental engineering, and computers have been established as curricular options. There are presently 336 undergraduates enrolled in our Department of Chemical Engineering.

The M.S. degree requires 27 semester hours of graduate work including six hours of thesis work and is normally completed within 18 months. There are presently 34 students enrolled in the M.S. degree program. The M.E. degree is a non-thesis degree which is intended to meet the needs of practicing engineers who are working full-time outside the University. The Ph.D. degree requires 30 hours of graduate level courses beyond the B.S. degree. There are presently seven students enrolled in the Ph.D. program.

TEACHING QUALITY

THE DEPARTMENT HAS STRESSED an undergraduate curriculum oriented towards process development since most of our undergraduates go directly into industry. It is a departmental policy not to accept our own undergraduates into our graduate program.

The quality which can be attained in a graduate curriculum depends in large part on the students in the program. Boulder's stimulating environment and a solid fundamentally oriented graduate curriculum have attracted outstanding students into our ChE graduate program. The median undergraduate grade point average of our entering graduate students during the past five years is 3.7/4.0.

We believe that the teaching quality in both our undergraduate and graduate programs is outstanding. There is significant tangible evidence to support this claim. For example, the full-time faculty in the Department have authored, co-authored, or edited 64 books. Included among these is the widely accepted text *Plant Design and Economics for Chemical Engineers* by Peters and Timmerhaus. In addition, several of our faculty have won major awards for contributions to teaching excellence in recent years. Professor Max Peters received the 1973 Lamme Award of ASEE and the 1979 Warren K. Lewis Award of AIChE. Both Max Peters and Klaus Timmerhaus have won

ASEE's George Westinghouse Award. Professors William Krantz and Ronald MacGregor have won the University of Colorado Teaching Recognition Award. In addition, Professors Krantz and Ronald West have won the College of Engineering Teaching Recognition Award. The excellent preparation which our students receive in process design is supported by having four of our students receive national recognition in the AIChE Student Design Problem Competition in recent years.

A most effective measure of a faculty's influence is the number of students who follow them into the ranks of engineering education. A number of our Ph.D. students are presently staffing chemical engineering departments throughout America. These include: Adel Al-Taweel (New Brunswick); Neil L. Book (Missouri-Rolla); Joseph N. Cannon (Howard); David E. Clough (Colorado); Michael B. Cutlip (Connecticut); H. Scott Fogler (Michigan); Henry W. Haynes (Mississippi); Russell F. Heckman (South Dakota School of Mines and Technology); Hal L. Hutchinson (Wyoming); David Kauffman (New Mexico); Robert L. Sandvig (South Dakota School of Mines and Technology); Jay J. Scheldorf (Idaho); and Richard L. Zollars (Washington State).

RESEARCH PROGRAMS

THE UNIVERSITY OF COLORADO IS in close proximity to five major national research facilities: the National Bureau of Standards (NBS); the National Center for Atmospheric Research (NCAR); the National Oceanic and Atmospheric Administration (NOAA); DOE's Solar Energy Research Institute (SERI); and DOE's Laramie Energy Technology Center (LETC). In addition, the presence of campus-based research institutes provides support for our research programs. These include the Cooperative Institute for Research in Environmental Sciences (CIRES) and the Institute for Arctic and Alpine Research (INSTAAR). Colorado is also an energy-rich state claiming the world's richest oil shale deposits, estimated to contain more than two trillion barrels of oil (this is more potential crude oil than is estimated to exist in the entire Middle East!), some 230 billion tons of subbituminous and bituminous coal, an estimated reserve of two billion barrels of recoverable crude oil, and 8.3 trillion cubic feet of recoverable natural gas. The presence of these major research facilities, research institutes, and enormous energy resources constitute a stimulating environment which has shaped the character

Gregory L. Klingler (left) of CU receiving the A. E. Marshall Award for his solution in the 1979 Student Contest Problem, and Max S. Peters receiving the 1979 Warren K. Lewis Award.

and promoted the quality of chemical engineering research at CU. These research programs are briefly described below:

Atmospheric and Geophysical Studies

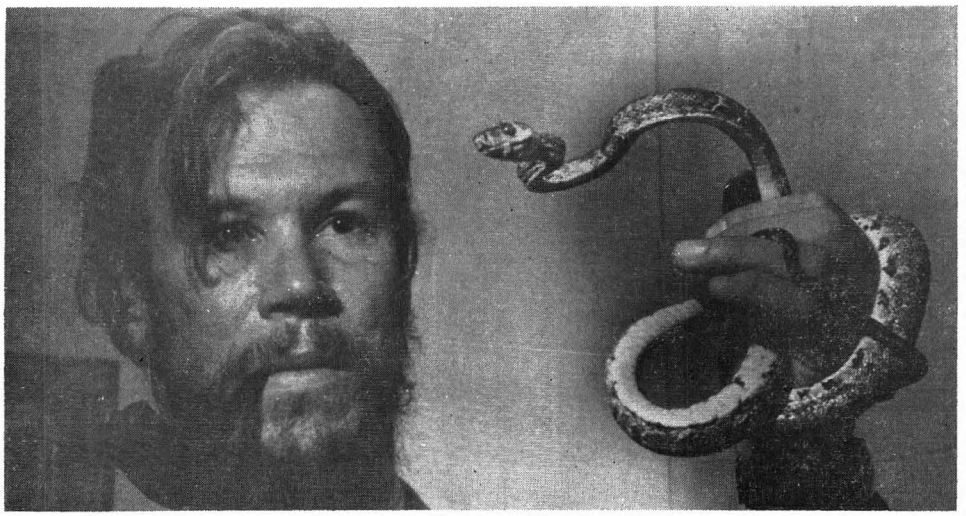
In collaboration with Dr. Nelson Caine of CU's Institute of Arctic and Alpine Research and Professor Robert D. Gunn of Wyoming's Department of Chemical Engineering, Professor Krantz is studying transport processes in permafrost. The alpine and arctic climate zones offered by the Rocky Mountains are essential to this research. Professor Sani is investigating small-scale atmospheric flows and transport over general terrain, and is developing a finite element two-dimensional atmospheric boundary layer model. This research is being conducted in conjunction with CU's Cooperative Institute for Research in Environmental Sciences in which Professor Sani holds a joint appointment.

Bioengineering

Our bioengineering program focuses on an engineering approach to sensory physiology and neuroscience. Professor Gamow is attempting to deduce the molecular structure of the living cell wall by cataloging the reproducible growth patterns of the giant unicellular fungus Phycomyces. His laboratory has shown that additional growth patterns can be created by mechanically deforming the living cell wall. These experiments have led to testable molecular models that appear to account for the structure, growth, and regulation of the living cell wall. The central thrust of Professor MacGregor's research on the electrical activity of brain networks is the illumination of how neuronal populations coordinate electrical signals into meaningful global patterns. This work involves computer simulation of large neural networks. He is also attempting to guide micro-electrode experimentation concerning the coordination of activity in neuronal populations.

Energy Engineering

Our most extensive graduate program concerns a broad research effort in energy-related studies. Professor Brown is studying the stimulation of coal gasification reactions by nonequilibrium excitation of the reactants, the creation of more active coal char by appropriate preparation



The bioengineering program at CU is focusing on an engineering approach to sensory physiology. Prof. Igor Gamow is studying the receptors in snakes whereby they "taste" heat.

methods, the mechanisms of catalytically promoting low-temperature gasification of coal, and the effect of diluent gases on coal gasification reactions. Professor Clough is studying the dynamics of fluidized-bed coal gasifiers. Professor Falconer is investigating sulfur poisoning of the catalysts used to make hydrocarbons from syngas. Professor Krantz, in collaboration with Professor Robert D. Gunn of Wyoming's Department of Chemical Engineering, has a program in underground coal gasification which is coordinated with the field tests of this technology being conducted by DOE's Laramie Energy Technology Center in Hanna, Wyoming. Professor Ramirez is studying the mechanisms of dispersion, adsorption, and interfacial tension insofar as they affect surfactant behavior in tertiary oil recovery. Professor Timmerhaus' research includes economic studies of alternate energy resources, the economic and thermodynamic evaluation of various cycles for power generation, investigation of energy conservation alternatives, and determination of the thermodynamic properties of liquefied natural gas and synthetic natural gas.

Environmental Engineering

The current emphasis in Professor Peters' research in heterogeneous catalysis is on the use of carbon-containing polymers for catalysts or reactants for the reduction of nitrogen oxides. He is also studying the reaction kinetics of photochemical reactions involving chlorofluorocarbons and nitrous oxide. Professor Ramirez is studying the leaching of pollutants into ground water from spent oil-retorted shale. Professor Sani is developing numerical techniques for solving the complex fluid mechanical problems associated with pollutant transport in the planetary boundary layer. Professor West's general area of research concerns water pollution control processes, especially solid-liquid separations.

Kinetics and Catalysis

In addition to his applied research in coal gasification kinetics cited above, Professor Brown is studying gas-adsorbate momentum and energy transfer in surface diffusion and heterogeneous catalysis. In collaboration with CU's Electrical Engineering Department, he is also studying electric effects in semiconductor catalysis. Professor Falconer is studying heterogeneous catalytic reactions on supported metal catalysts in order to understand reaction mechanisms and how they are influenced by catalytic properties. Methanation, structure-sensitivity of organic decompositions, and desorptions of molecules from supported catalysts are being studied with transient reaction techniques. He is also using ultrahigh vacuum techniques and Auger electron spectroscopy to study heterogeneous catalytic reactions on well-defined metals and alloys.

Process Dynamics and Control

Characterization of the time-dependent behavior of fluidized-bed processes is a focus of Professor Clough's research efforts. Theoretical and experimental studies are in progress which will lead to the development of dynamic mathematical models which will be used in the design of advanced control systems. Professor Clough is also concerned with the adaptive multivariable control of distillation columns. Professors Ramirez and Clough, in a joint effort, are investigating the on-line identification and control of distributed parameter systems with particular focus on the catalytic oxydehydrogenation of ethylbenzene to form styrene monomer.

Surface Phenomena

Professors Brown and Falconer's research on the solid-gas interface has been described elsewhere. Professor Krantz is interested in mass transfer at gas-liquid interfaces, the properties of dynamic interfaces, and the stability of flows having a free interface. Professor Ramirez' research in tertiary oil recovery is discussed above. Professor Sani is studying the stability of bounded systems with an active interfacial region and is also investigating electrochemical deposition and isolated pit initiation in corrosion.

Theory of Liquids and Thermophysical Properties

Professor Adjoint Howard Hanley, of the National Bureau of Standards, is using computer simulation to study the behavior and properties of pure fluids and mixtures in equilibrium and in non-equilibrium. He is particularly interested in the behavior of liquids under the influence of high shear. The technique of corresponding states is being applied to predict the properties of mixtures, especially at

a gas-liquid and liquid-liquid critical point. Professor Timmerhaus is investigating the properties of insulation systems for use in cryogenic applications.

These research programs have produced 305 technical publications during the past ten years. This is an average rate of 2.4 publications per year for each faculty member. The quality of our research programs has also been recognized by several major awards during recent years. Professor Klaus Timmerhaus received AIChE's Alpha Chi Sigma Award in 1968. Three Fulbright-Hays Fellowships have been awarded to our faculty in recent years: Professor William Krantz (1974); Professor Fred Ramirez (1976); and Professor Ronald West (1979). Professor Robert Sani was awarded a Guggenheim Fellowship in 1970 and Professor Krantz an NSF-NATO Senior Fellowship in Science in 1975. Two members of our faculty, Max Peters and Klaus Timmerhaus, have been named to the National Academy of Engineering.

COMMITMENT TO PROFESSIONAL SERVICE

THE IMPORTANT ROLE OF professional service was emphasized early in the history of our College of Engineering. Milo S. Ketchum, Dean of the College from 1905-1919, was among the first Presidents (1917) of the Society for the Promotion of Engineering Education (now ASEE). In 1924 the University of Colorado subsequently served as the host of the first Annual Convention of the Society to be held in the West.

This tradition of service to the engineering profession continues today. In particular, the Chemical Engineering Department at CU is noted for its commitment to professional service at the national level. It is one of two departments in the U.S. which can boast of having two former AIChE National Presidents among its active faculty, Max Peters (1968) and Klaus Timmerhaus (1976). In addition, it is among relatively few departments that have had two currently active faculty serve in a temporary capacity as administrators for NSF programs. Klaus Timmerhaus served as Head of the Engineering Chemistry and Energetics Section in 1972-73 and William Krantz served as Director of the Thermodynamics and Mass Transfer Program in 1977-78. Of the many advisory bodies on which members of the CU faculty have served, particularly noteworthy are Peters (1969-75) and Timmerhaus' (1978-81) services as AIChE representatives on the ECPD Board of Directors. Klaus Timmerhaus has also rendered invaluable service to *Chemical Engineering Education* as chairman of its Publication Board.

Our Department is also active in service at the international level. Professor R. Curtis Johnson, former chairman of our Department, became the first Dean of International Education at CU. He has been effective in strengthening CU's study-abroad programs and in promoting other cultural and technical exchange programs with foreign universities. Professor Krantz is presently serving on the Advisory Panel for the U.S. Council for the International Exchange of Scholars which administers the Fulbright-Hays Fellowship program. Professor Howard Hanley has been involved with the Marie Skladowska-Curie Program for scientific cooperation between the U.S. and Poland.

This service in the interest of our profession rendered by CU's Chemical Engineering Department has also been recognized by several major awards. R. Curtis Johnson, Max Peters, and Klaus Timmerhaus have been elected Fellows of the AIChE. Peters and Timmerhaus have also received the AIChE's Founders Award. Professor Hanley has been elected a Fellow of the Royal Institute of Chemistry. In addition, Professor Krantz received Special Achievement and Outstanding Performance Awards from NSF in 1978 for his service as Program Director.

EPILOGUE

FACULTY IN MOST ENGINEERING departments at our major colleges and universities are evaluated on the basis of their contributions to teaching, research, and professional service. It is appropriate then to evaluate the departments encompassing these faculty on the basis of these same three criteria. We in the Department of Chemical Engineering at the University of Colorado believe that this blend of teaching quality, research productivity, and professional service commitment is required for "world-class" excellence in chemical engineering education! □

ACKNOWLEDGMENT

This article on ChE at CU would not be complete without acknowledging the many companies and granting agencies which have supported our program throughout the years, and the present and past students, staff, faculty, and administration at CU whose efforts have contributed so much to the quality of our program. The author also gratefully acknowledges Mr. Martin Barber of CU for his assistance in providing the photographs used in this article, and Miss Ellen Romig for her assistance in preparing the final copy.

ChE educator

William H. Corcoran of Caltech

Prepared by
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California Institute of Technology
Pasadena, California 91125

WILLIAM H. CORCORAN HAS collected enough honors during his career as a chemical engineer and educator to fill several pages on a resume. But the award that means most to him is a handsome plaque hanging beside the door of his Caltech office and enscribed: "To our fearless leader: We promise to love, honor, and obey mass, energy, and momentum balances throughout our lives. Class of '77."

This plaque, enscribed with the names of all the students in Bill's senior Optimal Design of Chemical Systems course, is a token of the affection between him and his students; an affection undiminished by the copious amounts of work that he dispenses and the rigorous standards that he requires them to meet.

Bill's work as a teacher affords him great pleasure, but it is only one of the roles he has filled during his 37 years as a chemical engineer. He has been president of the American Institute of Chemical Engineers, Caltech's vice president for Institute relations and the executive officer of its chemical engineering department, an executive in the biomedical engineering field, and a consultant to the biomedical industry (he has consulted for the American Hospital Supply Corporation since 1952). Now Caltech's Institute Professor of Chemical Engineering, Bill has earned a reputation for energy and enthusiasm, hard work and self-discipline, superb organization and keen integrity, compassion for human need, and a sense of humor and a dry wit that include the ability to laugh at himself.

He has been president of AIChE, Caltech's vice president for Institute Relations and the executive officer of its ChE department, an executive in the biomedical engineering field, and a consultant to the biomedical industry.

He has been variously described by his colleagues as one who "is a prophet in the field of chemical engineering" . . . "is overwhelmingly supportive of people he believes in and never holds a grudge" . . . "is dedicated to his students and suffers when they suffer" . . . "possesses no tolerance for any kind of slop" . . . "rewards you when you do a job well by giving you more work" . . . "puts all he has into everything he does" . . . "is decisive without being oppressive" . . . "is a wonderful colleague who's always helpful" . . . "is an unguaranteed baritone" . . . and "is enormously forthright and willing to give you his honest opinion on most any issue (if you don't want it, don't ask)."

THE EARLY YEARS

BILL IS ONE OF THOSE rather rare individuals in his generation who is actually a native of Los Angeles. His father, a California farmer, died when he was a year old and he was raised by his mother, who worked as credit manager for a wholesale grocery company, and his grandmother,

a retired teacher whom he describes as "almost a mother and father to me at that time."

He attended Los Angeles public schools, including Norwood Grammar School a few blocks from the University of Southern California. In his neighborhood, at the vulnerable age of four, he began to form what would become a lifelong addiction to USC football.

His enthusiasm for the natural world, and his fascination with the way things worked, were stimulated at Fairfax High School by his biology and physiology teacher, Doris Siddall. So keen was her passion for nature, and so determined was she to give her students fresh insight into its marvels, that she frequently would rise at 3 a.m. to travel by Pacific Electric car to San Pedro to collect fresh samples of sea life from the tide pools to illustrate her lectures. "Her style was a tremendous inspiration to me," says Bill. "She was a living example of the impact of a teacher on her students."

Last year, after what he terms "40 years of thinking about it," he found Mrs. Siddall, now 87, and brought her to Caltech for a reunion with lunch and a look at the Institute's facilities. Meanwhile he had had other reasons to recall his high school days: In 1976 the Los Angeles School District honored him as one of its 50 outstanding graduates during the Bicentennial celebration. He shared recognition in the field of science and medicine with Nobel laureate Glenn Seaborg and astronaut Walter Cunningham.

With college approaching, Bill weighed careers in medicine and chemical engineering but chose the latter. He believes he is fortunate in the decision he made, although he has never lost his keen interest in medicine and has worked extensively in biomedical engineering. "But if I had become a doctor," he speculates, "I'd have lived and died with every patient."

At Caltech Bill studied hard but also found time to write for the school paper and to indulge his love for sports. He played four years of intercollegiate baseball and participated in all of the intramural sports, spending almost every afternoon on the practice field. Here he deepened a belief in the importance of keeping fit as essential for an effective life, and in the influence of physical vitality on emotional attitudes. This perspective is one that he often expresses to students whom he advises.

As a student, Bill found Caltech and its faculty and student body fascinating ("one of the great things about Caltech has always been the high density of interesting people here") and he elected to continue his graduate work at the Institute after earning his BS degree in 1941. During his first year as a graduate student he met Martha Rogers, secretary to chemical engineering professor Bruce Sage. The couple became engaged six weeks after their first date and they were married on Sadie Hawkins Day, exactly a year after that first date. Bill notes that among the many desirable traits that Martha brought to the marriage—including intelligence, wit, charm, beauty, and a love of all kinds of sports—she came equipped with a handy knowledge of chemical engineering terminology, thanks to her work in Sage's office.

Bill's graduate work was well under way during the fall of 1941 when World War II erupted to change the pattern. He joined Cutter

In 1976 the Los Angeles School District honored him as one of its 50 outstanding graduates . . . He shared recognition . . . with Nobel laureate Glenn Seborg and astronaut Walter Cunningham.

Laboratories in Berkeley as a development engineer in biomedical-chemical engineering. But in the fall of 1942 he was called back to the Caltech campus to become a research supervisor and development engineer for the National Defense Research Committee of the Office of Scientific Research and Development. He worked on processing propellant and interior ballistics for artillery rockets and for the Manhattan Project on the firing mechanism for the atom bomb.

With the war at an end he returned to graduate studies, working toward his PhD as a National Research Council Predoctoral Fellow. His graduate work completed in 1948 (he was one of the first two people to receive PhDs in chemical engineering from Caltech), he and Martha again left for Berkeley where he had accepted a position as director for technical development for Cutter Laboratories.

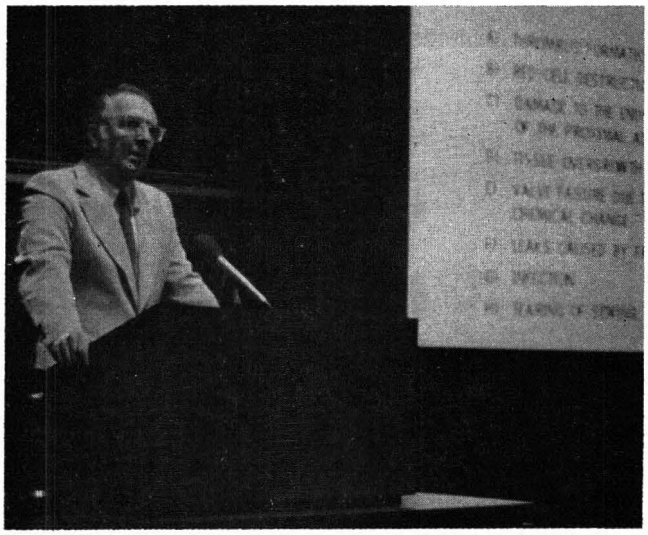
Predictably, Corcoran found work as a chemical engineer in industry to be exciting. "I love the atmosphere of industry," he says. "It is creative and there's an immediacy about the work that's very gratifying, whether, for example, it's drying blood plasma or manufacturing pharmaceuticals. A chemical engineer in industry can go to the end of the production line and see the product of his

efforts, and if that product makes a contribution to society, then the work is doubly exciting. Moreover, the hours, the pay, the support staff, and the equipment are usually better than at a university. To turn away from all this requires a very special reason."

AN ACADEMIC CAREER BECKONS

In 1952 he was asked to return to Caltech as an associate professor. He accepted. Making the decision was difficult, he acknowledges, but a very special reason prevailed; he couldn't pass up the opportunity to work with students. The rewards from teaching bright, creative young people filled with drive and enthusiasm and helping them develop their talents were irresistible. (Bill made just one more foray into industrial chemical engineering. He worked from 1957 to 1959 as vice president and scientific director for Don Baxter, Inc., while retaining a professorial appointment at Caltech.)

In addition to the chance to work with students, he cherished the independence of an academic



Dr. Corcoran describes his studies of heart valves at a seminar for alumni.

career. "My genes are very Irish," he explains, "and in my soul I'm a free spirit. I relish the opportunity to be myself. In the industrial world, if it becomes necessary for a company to make a 90-degree turn in direction, then its engineers must turn 90 degrees with it or get out. But at a university there's more freedom to choose one's own direction and little to block opportunities except oneself."

Bill then began an academic career that would carry him to the top of his profession. He combined teaching, research, and consulting, and a commitment to the evolution of the chemical engineering profession. He has expressed his views, and articulated his knowledge, via authorship or coauthorship of two books and more than 85 papers.

His capacity for leadership, hard work, and superb organization led to his becoming, at various points in his career, president of the AIChE, chairman of the council for the Engineers' Council for Professional Development (ECPD) and a member of its Board of Directors, national director of AIChE, chairman of the Engineering Education and Accreditation Committee of the ECPD, chairman of the Ad Hoc American Society for Engineering Education Committee on Review of Engineering and Engineering Technology Studies, chairman of the Air Force Institute of Technology Subcommittee Air University Board of Visitors, chairman of the Education and Accreditation Committee of the AIChE, a trustee and member of the Executive Committee of the Association of Independent California Colleges and Universities, and associate editor of the *Journal of Quantitative Spectroscopy and Radiative Transfer*.

He has also been a member of the Editorial Advisory Committee of *International Chemical Engineering*, the Editorial Committee of *Engineering Education*, the Advisory Board of *Industrial and Chemical Engineering Fundamentals*, and a member of the Board of Directors of the Huntington Institute of Applied Medical Research.

His contributions have won him honors including election as a fellow of the AIChE, the Lamme Award of the ASEE for excellence in his profession, the Western Electric Fund Award for excellence in teaching, the Founders Award from the AIChE for impact on his profession, and Educational Achievement Award from the California Society of Professional Engineers, an award from the Associated Students of Caltech for teaching excellence, and election to the National Academy of Engineering.

In 1969, in addition to a full load of teaching, advising, and research, he became vice president for Institute Relations with responsibility for Caltech's development and public relations programs at a time when universities throughout the country were faced with skyrocketing costs and the need for some painful belt tightening and ad-

"I relish the opportunity to be myself . . . at a university there's more freedom to choose one's own direction and little to block opportunities except oneself."

ditional funds. He accepted the position with the stipulation that he could continue to teach and do research. This July, after a decade, he relinquished that role to become Institute Professor of Chemical Engineering and to be responsible for examination of Caltech's and JPL's interactions in helping with the United States' energy program.

As vice president for Institute Relations, Bill guided Caltech toward the successful conclusion of a $130 million development campaign and, as administrative chief for a staff producing prodigious amounts of written materials, he found ample opportunities to implement his views concerning the need for clarity and precision in use of the English language. "Please clean this up by getting to the point," "Please eliminate 'tangible' as an adjective in describing dollars," and "No self-respecting grammarian would ever start any sentence with the very ambiguous 'it'," were among directives from him that were preserved and affectionately presented to him in a scrapbook when he retired from the position.

STUDENT CONTACT HAS TOP PRIORITY

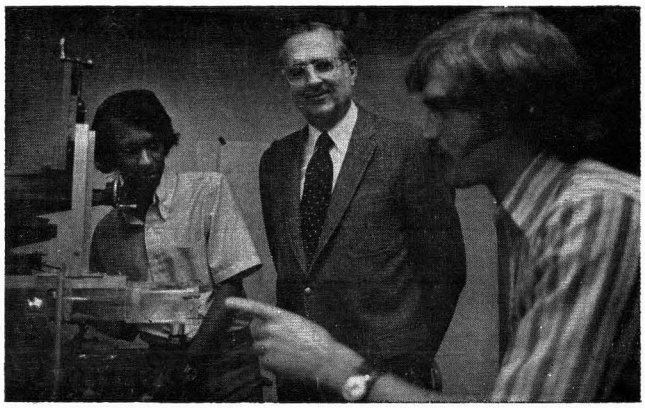
THROUGHOUT THIS PERIOD when he handled two full-time careers, he maintained two offices, one in Caltech's executive chambers and another in the chemical engineering building where he could be more easily accessible to the 30 or so students that he advised. He frequently told them, "Don't ever con me by telling me you can't find me. I'm available all the time." His staff soon learned that an appointment with an undergraduate ranked equally in importance with an appointment with a major donor, and that a trustee could be kept waiting if a student was undergoing a genuine personal crisis and needed extra counseling time.

During this era, fund-raising responsibilities often made it necessary for Bill to travel out of town. On these occasions he left his senior engineering class and his graduate students a number where he could be reached, inviting them to call him collect if they encountered a problem that couldn't await his return. "Call me any time, day or night," he always tells his students, adding, "but if you call after midnight you'd better have a relatively good question."

Because he believes in an effective counseling program for effective undergraduate education, he is known for his willingness to talk with his students about any problem from confusion over transport phenomena to a romance gone sour to how to budget one's time at a rigorously demanding academic institution. One student with a problem in the latter area was advised to write down a schedule showing how he planned to use his time during the coming week. The schedule revealed that the student was dating three girl friends, and Bill advised him to go the painful route of cutting down to one.

"I told him his first priority was to stay healthy," Bill says, "and his second to attend to his school work; that extracurricular activities would have to come third if he was going to be successful here."

As a teacher Bill is known for dispensing prodigious amounts of work ("I can't help feeling sorry for his students," says Martha, and a colleague adds, "He teaches them to be well organized; they have to be, to get his assignments in on time") and who tolerates no nonsense from procrastinators or goof-offs. But he is equally known for his willingness to give extensions of time when a student has a genuine problem, to go out of his way to make professional contacts for his students and to help them find jobs, and even to serve coffee and doughnuts on Friday mornings at an 8 o'clock class. ("This isn't a bribe to get you here," he'll tell them. "I just want to wake you up.")



W. H. Corcoran with graduate students Ajit Yoganathan and Russell Bone, examining measurements of the fluid mechanics of heat valves. (Yoganathan, at left, recently completed his PhD and is now an assistant professor at Georgia Tech.)

In his teaching, Bill consistently reminds his students that, through their impact on energy, the environment, food production, medicine, and so on, they are going to play roles as leaders in society whether they want to or not. "I believe it's my responsibility to remind them that they don't live under a rock," he says, "that they can't simply concentrate on chemical engineering and ignore the rest of what's happening around them. They should be able to read the Wall Street Journal, for example, and to understand the significance of its contents. They should be able to discern the connections between a decision of the President and the impact of that decision on engineering design and ultimately on society. I believe they get my point."

It was partly because of his desire to have students understand the economic and sociological aspects of engineering problems that Bill developed an introductory chemical engineering course for sophomores that was built around the study of problems based on hemodialysis and artificial kidneys. It allowed introduction to students of such basic concepts as mass, energy, and momentum balances, and stoichiometry, chemical equilibrium, and chemical kinetics, by applying them to treatment of kidney failure.

About one-third of three class hours per week was taught by a member of the chemical engineering faculty on basic principles of chemical engineering as applied to the problem of kidney dialysis; another one-third of the hours was devoted to lectures by medical and professional people on renal function and failure, the design and function of equipment for dialysis, and the social and economic problems of home and institutional dialysis. The remaining class time was spent on field trips to a hospital or manufacturing company to illustrate applications of the information presented in the course.

The artificial kidney demonstrates exceptionally fine examples of chemical engineering problems, Bill explains, and the costs of its maintenance and efficient use provide a good focus for the need to keep economics in mind while designing chemical systems. And finally, he adds, in dealing with human beings, students gain new insights into sociological needs and human problems—highly important for individuals who will make significant contributions to society through their creations.

In his work with senior students, Bill stresses the importance of an understanding of the nine elements of design: economics, material, energy and momentum transfer, chemical equilibrium, chemical kinetics, the properties of materials, process control, and safety. In the two terms of his senior course, Optimal Design of Chemical Systems, students apply these elements through independent problems and case studies. In the third term the course is entitled "Simulation and Design of Chemical Systems." In that course, the students simulate chemical processes, using Monsanto's FLOWTRAN programs. Bill doesn't give mid-terms or finals, considering them unproductive in a course devoted to problem solving. He says, "By the end of the year my students should understand the elements of design so thoroughly that they can explain the concepts to another person in their own words in a clear, unambiguous way. When they can do this, then they're ready to be employed as beginning engineers or to go on to graduate school."

Along with the many other responsibilities he's assumed, Bill has also found some time for excursions into musical comedy.

Bill's selection of an artificial kidney as a teaching device is symptomatic of his belief that chemical engineers had been too parochial in the scope of their efforts. "Chemical engineering is concerned with the control of chemical reactions to produce something useful for the benefit of society," he says. "Chemical reactions take place in many different places: in chemical plants, in food processing, in human kidneys, in rocket motors. And wherever these reactions occur, that's where the chemical engineer should be. I believe that members of the profession now recognize this, and that chemical engineering is now doing what it should be doing about diversifying its concerns."

Bill's own PhD work was associated with heat transfer in fluids, and as a faculty member at Caltech he worked on the experimental measurement of the coefficients of diffusion for heat transfer and momentum and on applied chemical kinetics. He has conducted work on the pyrolysis of hydrocarbons and is now working on the reaction kinetics of the desulfurization of fuel oil and coal. At the same time he continued work in bioengineering and biomedical engineering and was involved in the development of disposable hospital equipment, fermentation processes for penicillin and vaccines, and the development of

mass parenteral solutions and peritoneal dialysis. Most recently he has worked on the studies of artificial heart valves. During his teaching career he has counseled about 30 doctoral candidates who have gone on into leading roles in academic and industrial work.

SONG AND DANCE MAN—AND MORE

ALONG WITH THE MANY other responsibilities he's assumed, Bill has also found time for some excursions into musical comedy. He's been a regular in the Caltech Stock Company, a sturdy band of extroverted eggheads who lead double lives as professors, faculty wives, and other members of the Institute community. The musicals generally have commemorated anniversaries, retirements, and the awarding of Nobel prizes to Caltech luminaries, and Bill, picked for a solid baritone voice, has played such roles as a geologist, an illegal alien, a trustee, and a social worker, belting out lyrics like these: "Gneiss is a laminated metamorphic rock/the only stone a man can trust./ All the others are crude if not faintly lewd/They fill a good man with disgust./You can't trap us with your lapis/It's not gneiss."

"Some people think of Bill as an eminent educator," says Caltech's professor of English J. Kent Clark, who wrote the lyrics for all stock company productions. But to me, Bill will always be a song and dance man. A tremendous talent was wasted when he went into fund raising."

During the years that he's been deeply involved in professional activities, Bill has always remained close to his family. He and Martha have two children: Sally, 32, a mathematician and graduate of Pomona College and now the mother of two, who lives in Solana Beach, California, with her husband Ray Fisher, a plasma physicist from Caltech and now working for General Atomic in La Jolla; and their son, Bill, 29, who majored in soil science at Purdue and now lives (coincidentally) in Corcoran, California, where he is an operations manager for the J. G. Boswell Company. Bill and his wife, Leslie, are the parents of two young sons. As a college student Bill Jr. was a member of the Purdue football squad; Bill's colleagues began to notice that whenever the young man was to play in a Saturday game his father made an effort to be called to the Midwest on a speaking engagement that same weekend.

Bill's own love for sports—as spectator and participant—has remained undiminished throughout his career. He continues to follow USC football religiously (one student being stalked by Bill for an overdue paper claims to have diverted him from his objective by launching into a discussion of the fine points of Saturday's game), and he can describe the contributions of a quarterback with the authority he would use to explain which free radical is essential in a chemical reaction.

On vacation in Hawaii for three weeks each September he switches from sports spectator to participant. He wallows in golf and swims over a mile each day in the ocean. At home he enjoys badminton, he bicycles with Martha occasionally, and recently, intrigued with a burgeoning California fad, he bought a pair of roller skates to try around the neighborhood.

For many years, Bill revived his college baseball experience each year by pitching overhand softball in the faculty-senior game. This annual rite was eventually terminated, partly because of student discouragement over the fact that the faculty consistently won. He also kept his hand in baseball while his son was a teenager by managing Senior League and Babe Ruth League teams for boys 13 to 20. During the same period he and Martha taught high school Sunday school at St. James Presbyterian Church where they are members.

The Corcorans also have been involved in working on their avocado and lemon ranch near Fallbrook, California, an endeavor in which their children joined them when they were living at home. This environment gives Bill the chance to enjoy farming as a hobby and also to indulge a serious interest in the technology of agriculture.

Bill's tendency to find life full of exciting things to do has never diminished. And although his schedule is brim full, there are other activities he'd like to take on if he had the time. He'd like to master a musical instrument, for example, and to become proficient in Spanish (he's studied Latin, French, Spanish, and German). He reads for entertainment and would like to read more: "I'd read every moment of every day if I could." Bill feels activities like these he enjoys away from Caltech are essential. "We all have to recharge our batteries," he says. "If we don't, we miss really important parts of living."

His feelings about all the diverse elements that have characterized his interests, the challenges he has met, the places he has met them, is simple: "Everything that's happened to me has been good. I don't know why I've been so damn lucky!" □

ChE views and opinions

THE IMPORTANCE OF TEACHING FROM AN ASSISTANT PROFESSOR'S POINT OF VIEW

G. MICHAEL HOWARD
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Storrs, CT 06268

This paper was presented at the AIChE San Francisco meeting on behalf of J. Q. Doe, an Assistant Professor at Behemoth State University. It was written based on conversations with many Assistant Professors who each face some very hard decisions on what the importance of teaching should be in their career as a college professor.

I APOLOGIZE FOR NOT being here in person to present my remarks on the importance of effective teaching. However, discretion dictates that I remain anonymous. I feel that I do get along very well with the senior members of my department and the department chairman but this is a touchy subject and I could rub some of them the wrong way. I am now in my third year at Behemoth U. I got my Ph.D. from a well-known University after having spent two years in process development work in industry following my undergraduate degree. During my graduate work I did some paper grading as a teaching assistant but had no real classroom teaching experience. Various more peripheral experiences including coaching and tutoring led me to think that I would like to be a teacher and that I would enjoy the lifestyle associated with college teaching. The thoughts which are presented here are both anecdotal and personal and have led to my opinions on the importance of teaching.

I was fortunate to be looking for a teaching job during a time when colleges were looking for teachers. I had all the interview opportunities and offers that I wanted. At each interview I presented a seminar on my thesis research. I assume that this was to see if I could speak at all and to give the faculty a chance to find out if I knew a little bit about the area. The informal discussions I had were always about research interests, writing proposals and equipment needs. There was occasional discussion of my subject matter interest and teaching loads. The latter almost always with an implication of apologies for how much I *would* have to teach. There were no discussions about teaching style or methodology during the job hunting process.

My opinion . . . is that teaching effectiveness is the most important characteristic of a University

When I started I received no official instructions or advice about teaching or about classroom policies. I was simply told the two courses to which I was assigned. I got past outlines and examinations from departmental files and one of the faculty members did offer his problem solutions and pointed out some of the sticky sections of the book. This was very helpful, but there was virtually no interest shown in the launching of my teaching career by anyone except the same faculty member. He, I discovered, had a reputation for good teaching and seemed to be interested in whether or not I was running into any real difficulties. Since then, my teaching has developed through my own concerns.

I have observed that teaching is not a subject of general interest to the faculty. Lunchroom conversations, whether within the department or with mixed groups, range over: University politics and budgets, state and national interests, sports, money and investments, research projects and grants, and occasionally major curriculum issues. Teaching and what goes on in the classroom are almost never discussed casually by the faculty. Department seminars and school activities are also always of a technical or subject matter orientation. To be fair, whenever I have

asked selected colleagues about aspects of teaching they have been most responsive and helpful.

No one has come to observe my classroom efforts. I saw the department head, and on another occasion the dean, peeking in the back door of my classroom to get a glimpse of what was going on. There has been no review of my tests or grading policy, but then I haven't done anything extreme in this regard either. We do have a University-wide rating form which is sent to the students after each semester. About half of them return it. The results are given to me and to the department head and probably to the dean. I am now about a seven out of ten in everything and that seems to be fine with our head and the tenure committee. No one has ever really officially discussed what the results mean nor talked about using them to improve any aspect of what I do.

It does turn out that student rating of teaching is discussed every year when the results are received. However, the results are not taken very seriously. The usual kinds of "what do the students know" comments are heard. One professor in Economics gets some attention for his "lenient grading equals good rating" exposition which is made in the Faculty Senate every year. Many of the other arguments tending to devalue student ratings, such as those mentioned by McKeachie in his article in the October 79 AAUP Bulletin, are also heard. Emphasis here is on asking alumni since "you don't know good teaching til you've been out of school for awhile" and poor teaching forces students to learn for themselves. Of course no one has read the literature on evaluating teaching.

The equivalent of Mole's Mystery Hour is sure to be cited by someone as a final convincing example. The mole taught a graduate chemistry course. It is reported that some of his students had never even seen his face. He shuffled into class head down, opened his notebook on the front table, turned his back to the class, and proceeded to mumble toward the board while writing with his right hand and simultaneously erasing with his left. The students had little idea what he thought he taught other than the general subject for the day. Since he gave monsterous exams they were forced to study prodigiously on their own in order to be prepared for anything. As a result, those students who did take his course learned a phenomenal amount about the subject, typically at the expense of progress on anything else during that semester. Most students simply avoided the course. This type of story doesn't tend to promote good teaching.

The few people with great interest in teaching that I found from other departments would be overjoyed if they could get their colleagues to what they look upon as the engineering state of enlightenment in this area.

The situation around the campus is even worse. Engineers have long been interested in their students even if teaching as such is not a great concern. We do have ASEE and the various education interests within our professional societies. The few people with great interest in teaching that I found from other departments would be overjoyed if they could get their colleagues to what they look upon as the engineering state of enlightenment in this area. There is an underfunded teaching center on campus but it seems to be largely ignored. I have also been warned about a sad history of people who try to be visible and active in the cause of good teaching but don't get tenure. The School of Education, of course, does some things with respect to teaching but they are largely derided by the rest of the faculty.

I have argued that good teaching is not a very visible subject on campus and in the department. Clearly, it also is not a part of the reward system. Research is the obvious part of the faculty role that is all that teaching is not. There are so many cliches on this contrast that I cannot avoid using some of them. All of the non-tenured faculty receive letters from the dean and department head advising us of our progress after the annual performance review. My friends' experience is the same as mine. Regardless of how much research we seem to be doing we are urged and or threatened to publish more and get research grants. People seem to get tenure and promotions for research and are not downgraded for weak teaching performance. The converse is certainly not true. The story I know about a University letting go a very good researcher who was a terrible and disinterested teacher has the sad ending that the announcement of a prestigious research grant caused the terminal appointment decision to be reversed. Not surprisingly there had been no student protests in support of this assistant professor. The vice president's oft repeated statement that we expect our faculty to be good at both activities has a very hollow ring. In fact,

good research seems to lead to less and less teaching and more and more time away from campus and the students.

The publication system seems to make it easier to recognize research by providing a convenient bean counting procedure. We seem to be strangely reluctant to try to really evaluate teaching. As a profession we're willing to categorize colleagues as being poor researchers or uninterested in research. It seems to be much harder to acknowledge poor teaching. A psychology department faculty evaluation system discussed at the ASEE Summer School in 1977 showed this very clearly. Department faculty rated their colleagues over a full five point scale from 1.1 to 4.8 on research but restricted their range to 3 to 4.5 on the teaching evaluation. The poor teacher label is clearly one which is neither given nor accepted easily. Isn't this an anomaly in light of my earlier discussion?

My opinion formed over years as a student, alum, and now teacher is that teaching effectiveness is the most important characteristic of a University. It determines the attitude and learning of students which in turn determines the long term reputation of the University. Good teaching is also the source of tremendous satisfaction to the faculty. Sadly, the University reward system does little to recognize and develop effective teaching and in fact seems to actively discourage it. My own strategy, evolved after very painful soul searching, is to give teaching the minimum possible amount of my time. My teaching ratings should show me to be competent and I do prepare for classes and try to be friendly to the students. I try nothing new or different and I have the minimum possible number of office hours. These things take too much time and effort. It goes without saying that committee assignments, advising and similar unrewarded time consumers are avoided like the plague. I hope to let my interest in teaching come to the surface in the future, after I'm over the tenure-promotion hurdle. In the meantime I would be glad to have you visit me in the lab to talk about my research and maybe steering a few graduate students my way. If I'm not in the lab look for me in the library working on a proposal. Don't look for me in my office during the day—students might find me also and right now I can't take the time to help them learn. □

ChE letters

Dear Editor,

In the Winter 1980 issue of *CEE*, Cassano [1] discusses at length various "definitions" of the rate of reaction and finally concludes that 'The rate of reaction expression is the "sink" or "source" term in the continuity equation for multicomponent systems which will take into account the creation or destruction of the said species by chemical reaction." The unnecessary inclusion of the word *expression* spoils this otherwise satisfactory statement.

If *process rates* are distinguished from *rates of change*, the confusion regarding the "definition" of a rate, which exists in much of the literature and which is not greatly clarified by the above article, is easily avoided.

Process rates, such as the rate of a chemical reaction, are conceptual and mechanistic. They depend on the local environment, as described by the thermodynamic potentials alone in the special case of a homogeneous reaction. Process rates are ordinarily not measurable. Rather they are inferred with some unavoidable uncertainty from measured rates of change in space or time through the equations of conservation.

This distinction is discussed and illustrated extensively in my book [2]. It has also been noted by Dixon [3], Peterson (reference [16] of [1]) and many others.

The primary positive contribution of reference [1] is the illustration of the reduction of the equation of conservation of species to several of the special cases which are commonly used to infer rates of reaction from measured rates of change.

1. Cassano, A. E., "The Rate of Reaction: A Definition or the Result of a Conservation Equation?," *Chem. Eng. Educ.*, *14*, 14 (1980).
2. Churchill, S. W., "The Interpretation and Use of Rate Data: The Rate Process Concept", revised printing, Hemisphere Publishing Corp., Washington, D.C. (1979).
3. Dixon, D.C., *Chem. Eng. Sci.*, *25*, 337 (1970).

Best regards,
Stuart W. Churchill
The Carl V.S. Patterson Professor
University of Pennsylvania

ChE books received

"What Every Engineer Should Know About Patents," W. G. Konald, Bruce Tittel, D. F. Frei, and D. S. Stallard. Marcel Dekker, Inc., New York, 1979, 136 pgs, $9.75

This book, written for engineers, outlines the law of intellectual property with emphasis on patent law. Its objective is to provide a perspective of patents, trademarks, trade secrets, and related matters, without undue use of specialized legal language and terminology.

"Principles and Applications of Electrochemistry," 2nd ed., D. R. Crow, John Wiley & Sons, New York, 1979, 232 pages (paperback), $13.95.

This book presents in a simple and concise way the basic principles of electrochemistry that students require and some of its applications.

ChE class and home problems

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.

Our student readers, both graduate and undergraduate, are encouraged to submit their solution to the following problem to Prof. Robert L. Kabel, ChE Dept., Pennsylvania State University, University Park, PA 16802, before June 15, 1980 (please designate your student status on your entry). A complimentary subscription to CEE will be awarded in each category, to begin immediately or, if preferred, after graduation, for the best solutions submitted. (Penn State students are not eligible.) We will publish Prof. Kabel's solution in a subsequent issue.

PRAIRIE DOG PROBLEM

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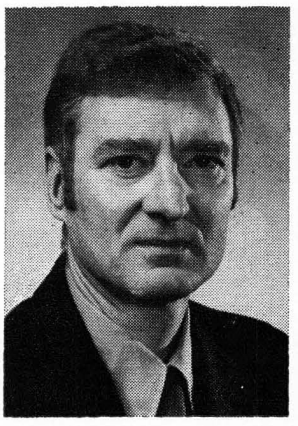
Prairie dogs live in underground burrows which are interconnected with tunnels as shown in Fig. 1. An important question immediately arises as to how the prairie dog architects provide ventilation for underground living during seasons of high activity and hibernation. You are requested to propose an explanation supported by calculations of how their tunnel ventilation system works.



Robert L. Kabel received his B.S. degree from The University of Illinois in 1955 and his Ph.D. from The University of Washington in 1961. From 1961-1963 he served n the U.S. Air Force Space Systems Division receiving the Commendation Medal for Meritorious Achievement. Since 1963 he has been at The Pennsylvania State University where he is Professor of ChE. He was at The Technical University of Norway (1971-72) and Pahlavi University in Iran (1978) as visiting professor and lecturer, respectively. He has served recently as Chairman of the AIChE's Chemical Engineering Education Projects Committee (1976-77) and the Central Pennsylvania section of the American Chemical Society (1970). His research centers around catalytic kinetics and air pollution meteorology. He is active in industrial consulting, flying, and squash.

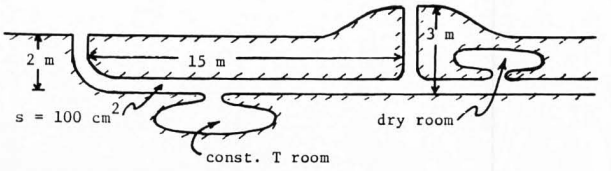


FIGURE 1

This problem illustrates a truism: The most difficult part of solving a problem is defining it. In formulating a ventilation mechanism you should consider the following discussion on prairie dog habits and habitats.

1. What is a prairie dog? (small rodent about 1/3 meter long)
2. Where do they live? (arid country, rather barren, sandy soil, some grasses in the region for food, etc.)
3. What do they need to live? (food—grasses, roots in burrows; water—not much; air)
4. How do they get their air? (molecular diffusion through soil and passage ways, going up to the top and breathing occasionally; replenishment in passage by some mechanism)
5. How much air do they need? (a single dog in a typical burrow has a 5-10 hour oxygen reserve)
6. What is the nature of burrow? (multiple holes, one in mound leading to a tunnel; spacing between mounds as shown in Fig. 1)
7. By what mechanisms could air be supplied?
   a. A "pig in a pipeline" theory might be

mentioned whereby prairie dogs moving through the tunnel drive the air out ahead of them and draw it in behind them. Everyone is familiar with the "whoosh" effect observed when subway trains come in. (My thought is that a tight fitting, fast moving, animal could well do this. But I expect that the animal fills only about 1/2 of the tube cross section. The tube radius is 5.64 cm versus an animal diameter of about 8-9 cm. Thus his sweeping efficiency may not be too good and a fairly continuous circulation might be required. Note also that this mechanism would not work during hibernation.)

b. The Bernoulli effect (high velocity, low pressure, and vice versa) is mentioned with no particular indication of the mechanism of getting high and low velocities. Perhaps there is a "mound" effect. There may be a variety of misconceptions about static air pressure; e.g., can the different elevations of openings induce flow simply because of Δp? In fact, Δp is balanced by gravity and it is impossible to vent pollutants to the vacuum of space.

c. A variety of chimney effects are possible; e.g. sucking at all openings due to wind across them and natural convection due to animal warmth below. The day-night cycle could give an effect similar to the breathing cave phenomenon.

d. Finally, if a tube is held vertically just above the ground, would there be flow through it? There will be a flow upward

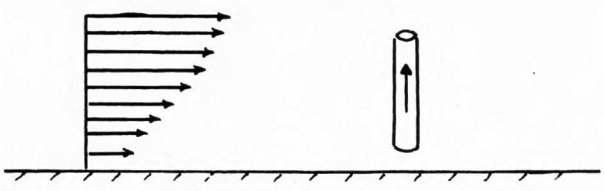


FIGURE 2. Boundary layer velocity distribution effect.

due to the boundary layer velocity distribution effect because of the low velocity and high pressure at the bottom and the high velocity and low pressure at the top. This Δp is greater than that inferred from hydrostatics.

You are now encouraged to use any of the above points in your explanation of the tunnel ventilation mechanism. □

ChE books received

"How to Find Chemical Information," R. E. Maizell, John Wiley & Sons, New York, 1979, 261 pages, $17.95.

Chemical information tools are in a constant state of change. This book will show you how to efficiently locate, use, and in some cases evaluate, chemical data.

"Fluid Catalytic Cracking with Zeolite Catalysts," P. B. Venuto and E. T. Habib, Jr., Marcel Dekker, Inc., New York, 1979 156 pages, $19.50

This book attempts to cover the broad scope of fluid catalytic cracking (using zeolite catalysts), with emphasis on the highly-coupled interactions of the process between the feedstock, the catalyst, the process hardware, and the desired products. Workers in petroleum refining and petro-chemical activities, and those interested in catalysis in general, will use this book as a resource and necessary research tool.

CLOSE ENCOUNTERS OF A SPARSE KIND*

ARTHUR W. WESTERBERG
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Pittsburgh, Pennsylvania 15213

The goal is to present methods for solving sets of nonlinear algebraic equations, e.g.:

$$f_1(x_1,x_2,\ldots x_n) = 0$$
$$f_2(x_1,x_2,\ldots x_n) = 0$$
$$\vdots$$
$$f_m(x_1x_2,\ldots x_n) = 0$$

Two cases are of interest

Square Case $n = m$
Nonsquare Case $n > m$

For the latter case n-m variables are degrees of freedom for the problem. Their values must be supplied from elsewhere.

We are interested in the case where the equations are sparse, i.e. each equation explicitly contains only a few of the variables. The literature contains two general approaches for solving:

- Tearing (with convergence acceleration).
- Newton-Raphson with sparse matrix methods.

Therefore we have two problems, $n = m$ and $n > m$, and two approaches to consider.

We shall first present an example problem, a flash calculation. For it we shall apply the essential ideas for solving by the tearing method and then by using the Newton-Raphson method.

*This paper was presented as the first annual tutorial lecture for the ASEE meeting held in Vancouver, British Columbia, in June, 1978. The material appears in more detail in the book Process Flowsheeting (Westerberg, Hutchison, Motard and Winter (1977)). It has been taught as part of an elective course on computer-aided process design to both seniors and graduate students in chemical engineering.

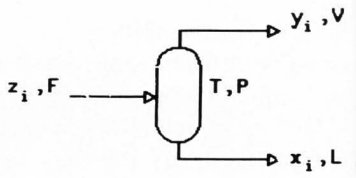

Fig. 1 A Flash Unit

EXAMPLE PROBLEM

A diagram for a flash unit appears in Figure 1. The model is as follows, where the physical properties are treated very simply.

Material Balance

$$y_iV + x_iL = z_iF \qquad i = 1,2,\ldots c \qquad (1)$$
$$V + L = F \qquad (2)$$

Arthur W. Westerberg received his degrees in chemical engineering at Minnesota, Princeton, and Imperial College, London. He then joined Control Data Corporation in their process control division for two years. In 1967 he joined the University of Florida where he remained for nine years. In 1976 he joined the faculty at Carnegie-Mellon University. He was Director of the Design Research Center from 1978 to 1980 and just became Head of Chemical Engineering this January.

Equilibrium

$$y_i = K_i x_i \quad (3)$$

Physical Properties

$$PK_i = P_i^o \quad \text{(Raoult's Law)} \quad (4)$$

Antoine's Equation for Vapor Pressure

$$P_i^o = 10^{(A_i - B_i)/(C_i + T)} \quad (5)$$

Other

$$\Sigma x_i - \Sigma y_i = 0 \quad (6)$$

$$\Sigma z_i = 1 \quad (7)$$

The problem we address next is to develop a solution procedure to solve these equations. We note that, for c = 3 components, the number of equations is 15 (Equation (1) 3 equations; (2) 1; (3) 3; (4) 3; (5) 3; (6) 1; (7) 1; for a total of m = 15 equations). The variables for the problem are:

$y_i, x_i, z_i, K_i, P_i, i = 1,2,3$ = 15 variables

V, L, F, T, P = 5 variables

For a total of n = 20 variables. Thus there are five variables in excess of the number of equations or n − m = 5 degrees of freedom for the problem.

Deriving a Solution Procedure for Square Case

We need first to reduce our problem to 15 equations in 15 unknowns. To do this we add five specifications. We shall set values for the five variables z_i, z_2, P, T, and F, a set of specifications corresponding to that for a so-called isothermal flash calculation. Figure 2 is an "incidence matrix" (or "occurrence matrix") for the 15 equations in the remaining 15 variables.

Our first task is to partition the equations if possible. For a sparse, square set of equations one will often find that a subset of the equations can be found which involves n_1 equations in precisely n_1 unknowns. These n_1 equations in n_1 unknowns can be solved first and by themselves. These n_1 equations and n_1 variables may then be deleted from the problem, leaving us with a set of $n-n_1$ equations in $n-n_1$ unknowns. We may again attempt to locate within this reduced equation set a further subset of n_2 equation in precisely n_2 unknown. Again, these may be solved next and by themselves. We can repeat this activity until no further reduction in the problem is possible. This task is known as partitioning the equations, and the order in which we then solve these partitions is called a precedence order. Solving a large problem as a sequence of small problems is clearly much easier to do.

The steps involved in partitioning a set of

We need first to reduce our problem to 15 equations in 15 unknowns. To do this we add five specifications. We shall set values for the five variables z_i, z_2, P, T, and F, a set of specifications corresponding to that for a so-called isothermal flash calculation.

equations are as follows. First, we assign a unique variable to each equation. This assignment is called an output assignment for the equations, and the circled variables in Figure 2 are such an assignment. For a small problem finding an output assignment can be done quickly by hand. For larger problems one may reformulate the problem as an assignment problem in linear programming and solve using the very efficient algorithms available for that particular problem type. Note that we have required an explicit output assignment here, that is, one in which each assigned variable

	y_1	y_2	y_3	x_1	x_2	x_3	z_3	V	L	K_1	K_2	K_3	P_1^o	P_2^o	P_3^o
f_1	①			1				1	1						
f_2		①			1			1	1						
f_3			1			1		1	①						
f_4								①	1						
f_5	1			①						1					
f_6		1			①						1				
f_7			1			①						1			
f_8										①			1		
f_9											①			1	
f_{10}												①			1
f_{11}													①		
f_{12}														①	
f_{13}															①
f_{14}	1	1	①	1	1	1									
f_{15}							①								

FIGURE 2. Incidence Matrix for Square Case. Circled incidences indicate an "output assignment" for the equations.

must appear explicitly within the equation to which it is assigned.

If an explicit output assignment has been found for the equations, then one can use path tracing algorithms to find the partitions and the precedence order for the partitions. To implement a path tracing algorithm we first establish a precursor list for the variables in our problem.

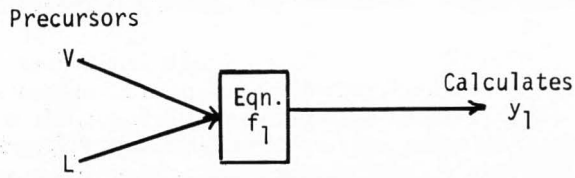

FIGURE 3. Information Flow for an Equation.

Figure 3 illustrates the essential ideas behind this precursor list. Figure 4 is a completed precursor list for the flash problem. Note that each equation is identified by its assigned output variable. The precursors to that variable are the other variables occurring in the equation. For example, equation f_1 has an assigned output variable y_1. The other three variables appearing in equation f_1 are x_1, V and L. In order to calculate y_1 using equation f_1 we would need to have values x_1, V and L. With a precursor list for our equations we may readily execute a path tracing algorithm to find the groups of equations which form the partitions for our equation set. We proceed as follows.

Variables	y_1	y_2	y_3	x_1	x_2	x_3	z_3	V	L	K_1	K_2	K_3	P_1^o	P_2^o	P_3^o
Precursors	x_1	x_2	y_1	y_1	y_2	y_3	-	L	y_3	P_L^o	P_2^o	P_3^o	-	-	-
	V	V	y_2	K_L	K_2	K_3			x_3						
	L	L	x_1						V						
			x_2												
			x_3												

FIGURE 4. Precursor List for Flash Problem.

Path tracing involves tracing through the precursor lists, starting with any variable.

y_1 has precursor x_1 which has precursor y_1 or

$y_1 \leftarrow x_1 \leftarrow y_1$

Clearly y_1 and x_1 are in an "information" loop; i.e., they each require the other to be calculated. We thus merge them and their precursor lists and treat them as a single item on our list. Thus

$(y_1x_1) \leftarrow V \leftarrow L \leftarrow y_3 \leftarrow y_1$

Clearly (y_1x_1) VLy_3 are also in a loop.

Continuing

$(y_1x_1VLy_3) \leftarrow K_1 \leftarrow P_1^o$ no precursor.

Thus P_1^o may obviously be calculated first and by itself. It is deleted from all lists and placed first on our list of partitions. If we were to continue we would ultimately find the partitioning and precedence order implied by the reordered incidence matrix in Figure 5. We note only the last partition involves more than one equation in one unknown. For each partition we must then derive a solution procedure. The last eight equations in eight unknowns require simultaneous solution.

Tearing Approach

Tearing is used to locate a solution procedure which requires one to guess only a few (say t) of the variables and then use n-t of the equations to calculate directly the values of the remaining n-t variables in terms of those guesses. The t unused equations may then be used as error functions which should be zero if our guesses are correct. If not zero we need to reguess. If we assume that each variable may readily be calculated in terms of the remaining variables appearing in the equation, then the following algorithm may be used.

Algorithm (A quick and dirty, but effective, algorithm.)

1. Select as the next equation the one containing the fewest new variables. Repeat until all equations selected.
2. Select strategically among new variables introduced with each equation one to be calculated by it. If no new variables are introduced, select the latest variable introduced earlier which remains unassigned and which has a cause/effect relationship to new equation.

Applying this algorithm gives the following result:

	P_1^o	P_2^o	P_3^o	z_3	K_1	K_2	K_3	y_1	y_2	y_3	x_1	x_2	x_3	V	L
f_{11}	[1]														
f_{12}		[1]													
f_{13}			[1]												
f_{15}				[1]											
f_8	1				[1]										
f_9		1				[1]									
f_{10}			1				[1]								
f_1								1			1			1	1
f_2									1			1		1	1
f_3										1			1	1	1
f_4														1	1
f_5					1			1			1				
f_6						1			1			1			
f_7							1			1			1		
f_{14}								1	1	1	1	1	1		

FIGURE 5. Partitions and their Precedence Order for Flash Problem.

CHOOSE EQUATION (Step 1)	NEW VARIABLES (Step 1)	ASSIGNED VARIABLE (Step 2)
f_4	L, V	L
f_1	y_1, x_1	y_1
f_5	-	x_1
f_2	y_2, x_2	y_2
f_6	-	x_2
f_3	y_3, x_3	y_3
f_7	-	x_3
f_{14}	-	V

which implies the following solution algorithm.

1. Guess V
2. Solve f_4 for L
3. Guess x_1
4. Solve f_1 for y_1
5. Evaluate f_5
6. If f_5 not zero, reguess x_1 and iterate from 4
7. Guess x_2
8. Solve f_2 for y_2
9. Evaluate f_6
10. If f_6 not zero, reguess x_2 and iterate from 8
11.
12.
13. ditto for x_3, y_3
14.
15. Evaluate f_{14}
16. If not zero, reguess V and iterate from 2

One could also solve by saving the evaluation of f_5 (Step 5), f_6 (Step 9) and f_7 (Step 13) until the end and evaluating all three with f_{14}, then reguessing V, x_1, x_2 and x_3 simultaneously.

Note that equations (f_1, f_5) are linear in x_1 and y_1 and could be solved directly as a pair of linear equations. Thus the iteration in Step 6 is not necessary. (f_2, f_6) and (f_3, f_7) are also linear in (x_2, y_2) and (x_3, y_3), respectively.

Newton-Raphson With Sparse Matrix Methods

The Newton-Raphson method is to linearize our equations about a current guess:

$$f_1(x_1 + \Delta x_1, x_2 + \Delta x_2, \ldots x_n + \Delta x_n) \approx f_1(x_1, x_2, \ldots x_n) + \frac{\partial f_1}{\partial x_1}\Delta x_1 + \ldots + \frac{\partial f_1}{\partial x_n}\Delta x_n$$

$$f_2(x_1 + \Delta x_1, \ldots x_n + \Delta x_n) \approx f_2(x_1, x_2, \ldots x_n) + \frac{\partial f_2}{\partial x_1}\Delta x_1 + \ldots + \frac{\partial f_2}{\partial x_n}\Delta x_n$$

$$\vdots$$

etc

$$\mathbf{f}(\mathbf{x} + \Delta\mathbf{x}) \approx \mathbf{f}(\mathbf{x}) + \left(\frac{\partial \mathbf{f}}{\partial \mathbf{x}^T}\right)_{\mathbf{x}} \Delta\mathbf{x}$$

The approach is to find the change required in $\mathbf{x}$ such that the linearized equations become zero at $\mathbf{f}(\mathbf{x} + \Delta\mathbf{x})$. We thus get the Newton-Raphson equations:

$$\left(\frac{\partial \mathbf{f}}{\partial \mathbf{x}^T}\right)_{\mathbf{x}} \Delta\mathbf{x} = -\mathbf{f}(\mathbf{x})$$

which are a set of linear equations. The solution algorithm is as follows:

Algorithm

1. Guess $\mathbf{x}$
2. Evaluate $\mathbf{f}(\mathbf{x})$ (which should be zero at solution)
3. Evaluate Jacobian matrix $\left(\frac{\partial \mathbf{f}}{\partial \mathbf{x}^T}\right)$ at $\mathbf{x}$.
4. Solve NR eqns for $\Delta\mathbf{x}$
5. Let $\mathbf{x}$ be replaced by $\mathbf{x} + \Delta\mathbf{x}$ and iterate from (2) until $\mathbf{f}(\mathbf{x})$ is very small.

The Jacobian matrix has most coefficients equal to zero; it is very sparse. It should be solved using sparse matrix methods. For the flash equations the Jacobian matrix is as follows.

$$\frac{\partial \underline{f}}{\partial \underline{x}^T} = \begin{array}{c} \\ f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_{14} \end{array} \begin{array}{c} \begin{array}{cccccccc} y_1 & y_2 & y_3 & x_1 & x_2 & x_3 & L & V \end{array} \\ \begin{bmatrix} V & & & L & & & x_1 & y_1 \\ & V & & & L & & x_2 & y_2 \\ & & V & & & L & x_3 & y_3 \\ & & & & & & 1 & 1 \\ 1 & & & -K_1 & & & & \\ & 1 & & & -K_2 & & & \\ & & 1 & & & -K_3 & & \\ -1 & -1 & -1 & 1 & 1 & 1 & & \end{bmatrix} \end{array}$$

which is then evaluated in each iteration at the current values of all the variables.

The essential idea in using sparse matrix methods is to develop a pivot sequence for solving the linear equations which creates the fewest new nonzero elements in our coefficient matrix as we solve the equations. Each nonzero coefficient requires added work in terms of multiplies and adds which we desire to avoid. A very quick and dirty algorithm for finding a better pivot sequence is as follows.

Algorithm (one of many)

1. Select row with fewest entries
2. Select in that row, column with fewest entries
3. If selected element not almost zero, select as next pivot and proceed.

Figure 6 shows this pivot selection algorithm applied to our flash equations for the first two of

It is very easy to solve several hundred to a few thousand sparse linear equations.

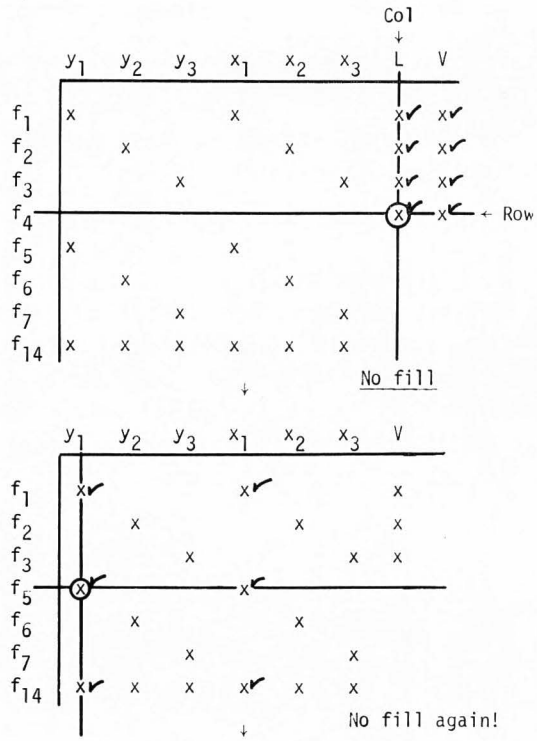

FIGURE 6. The First Two Pivot Selection and Elimination Steps for Flash Problem.

the eight pivots selected. The check marks indicate coefficients which are altered when using the selected pivot to eliminate the nonzeros in the pivot column during Gaussian elimination. The first pivot selected is in the row for f_4 and in the column for L. Gaussian elimination then requires us to zero out all other nonzeros in the pivot column. This elimination is done by subtracting the appropriate multiple of the pivot row from all rows having a nonzero in the pivot column. Only those elements checked will be changed by this step, and hopefully only a few of them will be changed from zero to nonzero, i.e. "filled". Here all changed elements are already nonzero and no nonzeros "fill" in either step. If we continue we would discover only one nonzero fills by the time all eight pivot/elimination steps are completed. One could count the numbers of multiplications and additions needed to do the forward elimination here and discover the numbers are very small relative to handling all the zero valued coefficients too.

It is very easy to solve several hundred to a few thousand sparse linear equations.

Solving Nonsquare Equation Sets

A simple approach is to skip all partitioning and precedence ordering steps. Then the left over variables (those never assigned or pivoted) become the decision variables for the problem.

Other Topics

We have so far presented only a part of the material needed to solve sparse nonlinear equations. We should also present material on each of the following topics.

1. Methods to reguess tear variables, i.e.:
   - Secant Method (1 variable)
   - Generalized Secant Method (n variables)
   - Broyden's Method (n variables)
2. What to do if $||f||$ does not decrease after a step is taken in the N-R method, e.g.
   - take a smaller step in N-R direction.
   - use $||f||^2 = \sum_{i=1}^{n} f_i^2$ as an objective and seek a new direction more in the direction of steepest descent for this objective while also taking a shorter step (Levenberg/Marquardt algorithm)
   - use "continuation" method which converts N-R problem to one in integrating ODE's.
3. Scaling
   For each variable, determine a "nominal" value, then
   - Scale each equation so a typical term using nominal variable values is about unity.
   - Scale each variable so its nominal value is about unity.
4. Rewrite equations to avoid divisions (division by zero is fatal), e.g.:
   - For $e^{b/T} - T = 0$, let $y = b/T$ (a new variable) and then replace the single equation with the two equations
     $e^y - T = 0$
     $yT - b = 0$
   - For $ln\ x - x = 0$
     Use $y = ln\ x$ and replace equations with
     $e^y - x = 0$
     $y - x = 0$

In this case *ln* x does not itself involve division but, when one forms the Jacobian element $\partial f/\partial x = 1/x - 1$, we have a division, which if x becomes zero will destroy the N-R equations by giving an infinite coefficient.

SUMMARY

Advantages/Disadvantages of Tearing vs. N-R with Sparse Matrix Methods

- Tearing is the more commonly used method.
- Tearing requires much less computer storage, usually.
- Tearing can be made quite efficient, particularly if all variables to be iterated are converged together, rather than solved with loops imbedded inside loops.
- Newton-Raphson approach is really very good if done correctly. We regularly solve hundreds of equations in 5 to 10 iterations total.
- The AERE Harwell subroutine MA28* is readily available to perform all the sparse matrix-equation solving portion of the problem.
- N-R requires Jacobian elements be evaluated or estimated. We find this easy to do because we add new variables to keep the algebra simple.
- Newton-Raphson approach permits sensitivity calculations to be performed easily and for little computational effort. □

REFERENCE

Westerberg, A. W., H. P. Hutchison, R. L. Motard, P. Winter, *Process Flowsheeting*, Cambridge University Press, Cambridge, England (1979).

*Contact: Numerical Analysis Group, Bldg. 8.9, AERE Harwell, OX11RA, England. The routine MA28 is part of the Harwell library of scientific routines which is available for £150. (Very cheap at that price.)

In Memorium

JOHN D. STEVENS

John D. Stevens, professor of Chemical Engineering at Iowa State University, died April 1, 1980, after a short illness. He was a faculty member at Iowa State for 15 years, during which time he received several teaching awards including the Western Electric Fund Award. He had served as National President of Omega Chi Epsilon. Dr. Stevens published several papers in the area of emulsion polymerization and crystallization.

ChE conferences

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August 18-22, Davos, Switzerland
For further information: Dr. Gary Poehlein, ChE Dept., Georgia Institute of Tech., Atlanta, GA 30332

UTILIZATION OF THE RECYCLE REACTOR IN DETERMINING KINETICS OF GAS-SOLID CATALYTIC REACTIONS

STEPHEN C. PASPEK, ARVIND VARMA AND JAMES J. CARBERRY
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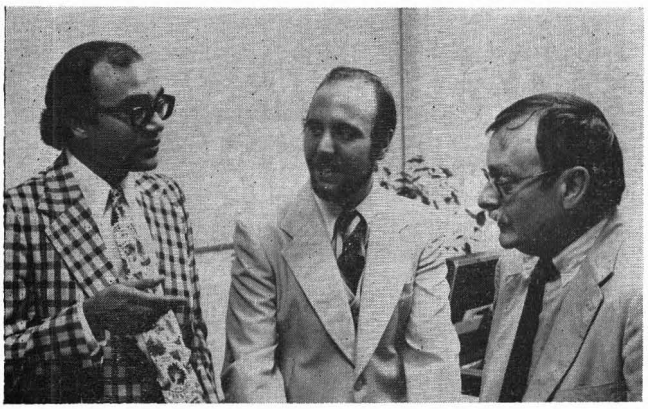
CATALYSIS AND REACTION modeling comprise a substantial portion of many reaction engineering courses, as well as being subjects of considerable industrial interest. Classroom lectures in this area of instruction are, with greater frequency, being supplemented by laboratory experiments. Several experiments, suitable for an undergraduate laboratory course, have previously been described. These have included both homogeneous reactions (typical examples being saponification reactions [16, 17], and the popular reaction of $Na_2S_2O_3$ with H_2O_2 for demonstration of reactor stability described by Schmitz [13]) and heterogeneous reactions (of which hydrocarbon or methanol oxidation on Pt wire [1, 6], alcohol dehydration on alumina in a batch [9] or fixed bed reactor [11], and ethylene hydrogenation on a Pt coated tube wall [2] are typical examples.)



The conservatively clad **Arvind Varma** (left), received his PhD at Minnesota under the direction of Neal Amundson. Varma also immersed himself in experimental work at the University of Minnesota under Aris McPherson Rutherford, noted distillation expert. The chap dozing on the right is **J. J. Carberry** (PhD, Yale), who is no doubt contemplating his co-authorship with Aris McPherson Rutherford of the monograph "Aquinas, Boethius and their Indebtedness to the Gill Report" to be published by the University of Houston Athletic Department. The fellow in the middle who did all the work reported here is **Steve Paspek** (PhD, Notre Dame 1979). This paper is based upon Steve's undergraduate senior year project. Steve is now with SOHIO where it is hoped that their equipment and instrument budget is commensurate with his Ambrosian tastes which nearly bankrupted Notre Dame.

While experiments involving homogeneous liquid phase reactions are relatively routine, formidable difficulties exist in the accurate modeling of solid catalyzed gas phase reactions. The majority of these problems can be attributed to gradients of temperature and concentration within the catalyst pellet and the reactor; such gradients frequently mask kinetic data to the point of rendering it useless. While it is difficult to design a perfect laboratory scale reactor to determine the kinetics of a gas-solid catalytic reaction, this paper indicates that an external recycle reactor will economically eliminate gradients for a number of gas-solid heterogeneous systems.

COMMON BENCH SCALE REACTORS

REACTORS IN LABORATORY use fall into four general categories: fixed bed reactors (including integral and differential types), pulsed reactors, agitated reactors, and recycle reactors. Excellent reviews of the various reactor types and their merits are given by Weekman [15] and by Doraiswamy and Tajbl [8]. Some serious difficulties inherent to the first three categories of reactors are presented below.

The integral packed bed reactor can rarely be operated in an isothermal fashion. At even moderate enthalpies of reaction, substantial amounts of heat are generated, creating both radial and axial temperature gradients. Zoned heat control, as illustrated by Viselov et al. [14] can minimize axial temperature profiles, but cannot mitigate radial gradients. Furthermore, the change of gas com-

While it is difficult to design a perfect laboratory scale reactor to determine the kinetics of a gas-solid catalytic reaction, this paper indicates that an external recycle reactor will economically eliminate gradients for a number of gas-solid heterogeneous systems.

position with bed depth leads to severe concentrational gradients, making the acquisition of meaningful kinetic data very difficult.

Use of the differential packed bed reactor is an attempt to minimize gradients by operating at extremely low conversion levels. This effectively limits the amount of heat generated, allowing near-isothermal operation. However, as noted by Weekman [15], extremely precise analytical techniques are required to measure the minute differences between the feed and effluent streams. For multicomponent systems this problem is intensified.

The pulse reactor yields differential results at relatively large conversion levels. However, the results are characteristic of only the initial catalytic response; the reactor cannot be operated in steady state. Furthermore, Makar and Merrill [10] note that the concentration of reactant species upon the catalyst surface changes as the pulse is forced through the reactor by the inert carrier, thus masking the true rate-concentration functionality.

Agitated reactors include the spinning-basket configurations developed by Carberry [12] and Doraiswamy [7], as well as internal recycle configurations popularized by Berty [3] and Bennett [4]. By virtue of severe agitation within the reaction vessel, the gas phase is mixed to a uniform composition and temperature. In the internal recycle reactors, the stationary catalyst bed allows direct measurement of the catalyst temperature. However, in the spinning basket design, the actual catalyst temperature cannot be measured; it must be inferred from the rate of reaction, the heat of reaction, and the rates of heat and mass transfer within the reactor. Unfortunately, the actual gas velocity relative to the catalyst pellet cannot be determined, and the standard correlations for heat and mass transfer rates cannot be applied to the system. Furthermore, both the spinning basket and internal recycle configurations involve a rather elaborately machined (and hence expensive) reactor vessel, as well as high temperature rotating seals.

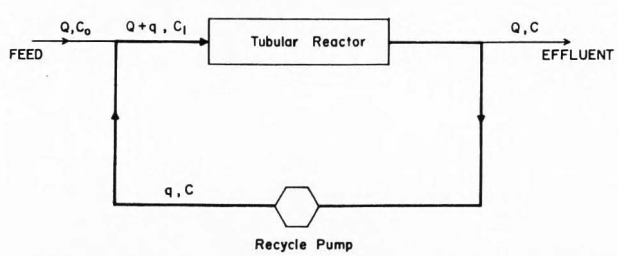


FIGURE 1: Schematic of external recycle reactor system.

EXTERNAL RECYCLE REACTOR

THE EXTERNAL RECYCLE REACTOR (Fig. 1) consists of a small isothermal tubular reactor coupled with a bellows-type recycle pump. The per pass conversion in the tubular reactor is quite low, approaching that of a differential reactor, and minimizing the amount of heat generated. However, by recycling a large portion of the effluent through the fixed catalyst bed many times, the overall conversion level is raised to that of an integral reactor. The reactor construction, detailed below, involves only readily available stainless steel tubing and Swagelock fittings; no machining is required.

The gas velocity relative to the catalyst particles can be easily determined, allowing the use of standard heat and mass transfer correlations for fixed beds. In addition, above a certain minimum rate, the gas velocity can be varied to suit the reaction system without effecting kinetic measurements. The recycle ratio R is defined as the ratio of the volumetric flow rate of recycled effluent/feed; as R increases, the reactor behavior approaches that of a CSTR.

A material balance around a recycle reactor for a first order reaction yields the expression

$$\text{Rate} = \frac{C_o}{\theta}\left[1 - \frac{\exp(-k\theta/R + 1)}{(1 + R) - R\exp(-k\theta/R + 1)}\right] \quad (1)$$

where C_o is the reactant concentration in the feed, k is the rate constant, and θ is the holding time (i.e., catalyst bed volume/volumetric feed rate). In the limit of $R \rightarrow \infty$, this expression reduces to

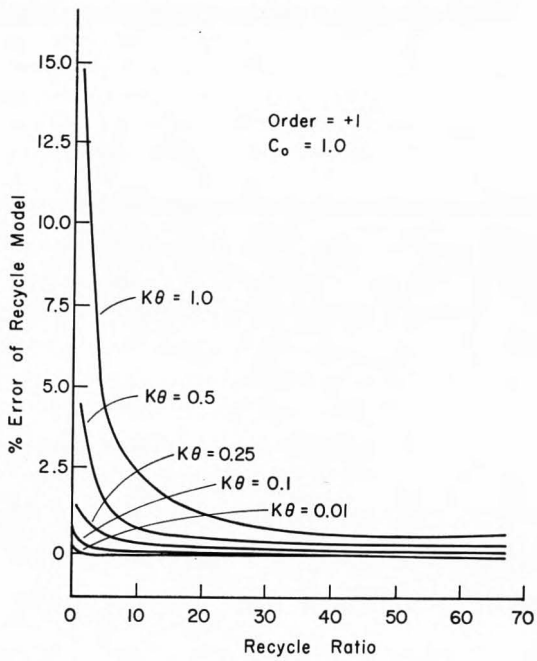


FIGURE 2: Plot of relative error between CSTR model and recycle reactor model for finite recycle ratios.

the CSTR rate expression

$$\text{Rate} = (C_o - C)/\theta \qquad (2)$$

The error between these two rate expressions is plotted in Fig. 2 for finite values of R. In general, the error is less than 1% for values of R greater than 25.

The instructional merit of the recycle reactor is that by operating with recycle ratios from 0 to over 25, plug flow to CSTR behavior becomes manifest, although complete isothermality is not guaranteed at recycle ratios less than 25.

EXPERIMENTAL DETAILS

THE REACTION VESSEL AND the preheater are 1.25 x 35 cm. SS tubes. The reactor tube is packed with active catalyst, while the preheater tube is filled with inert alumina pellets to promote mixing. Both tubes are held at constant temperature in individually controlled electric tube furnaces. Thermocouples are inserted into the gas stream at the exit of the preheater and the reactor through standard Swagelock fittings.

The recycle pump* is a metal bellows pump designed for high temperature operation, with a nominal capacity of 600 scc/sec. A standard arrangement of valves, rotameters, etc. is employed to control the reactor feed, admitted to the preheater at room temperature and atmospheric pressure.

Cooling coils quench the reactor effluent to reduce pump wear. Both the reactor feed and effluent compositions are determined via gas chromatography. The effluent sample is taken from the discharge side of the recycle pump; due to the pump's high suction, the inlet pressure is too low to allow flow through the chromatograph sample valve. Volumetric flow rates are determined by a mass flow meter or a soap film meter.

The recycle reactor can be easily automated by the addition of several cam timers, solenoid valves, and automatic needle valves. To determine isothermal kinetics, one must measure the reaction rate at a number of different reactant concentrations. This involves setting a feed rate and concentration, allowing the system to stabilize and equilibrate, and then sampling the feed and effluent streams to accurately determine their compositions. The reaction rate is calculated as the difference in composition divided by the holding time. A new feed composition or net flow rate is then selected, and the process is repeated.

Automatic operation was achieved by installing timer controlled solenoid valves on the feed and effluent lines, which periodically admitted samples to a gas chromatograph. The feed concentration was varied by coupling a small 1 RPM motor to a standard 10 turn needle valve. A cam timer activated the motor for a fixed period of time (i.e., 10 seconds) resulting in a fractional opening or closing of the valve, with the subsequent change in feed composition. The net reactor flow rate was continuously monitored by an electronic mass flow meter. However, the flow rate could also be measured with a soap film meter, and assumed constant for small changes in the

The external recycle reactor consists of a small isothermal tubular reactor coupled with a bellows-type recycle pump. The per pass conversion in the tubular reactor is quite low, approaching that of a differential reactor, and minimizing the amount of heat generated.

*Recycle pump available from Metal Bellows Corporation, 1075 Providence Highway, Sharon, Mass. 01067. Model MB-158HT was used in the apparatus.

minor reactant flow rate.

A schematic of the apparatus appears in Fig. 3.

APPLICATION OF THE RECYCLE REACTOR TO CO OXIDATION KINETICS

THE CATALYTIC OXIDATION of CO to CO_2 over noble metals is an interesting reaction because of the curious dependence of rate upon CO concentration (in excess O_2):

$$\text{Rate} = \frac{kC}{(1 + KC)^2} \qquad (3)$$

The kinetics, then, are of positive order for low CO concentrations, and change to negative order at CO concentrations greater than approximately 1%. Typical data for supported platinum are shown in Fig. 4.

Rate constants are easily determined by a least-squares fit of the rearranged rate expression:

The recycle reactor can be easily automated by the addition of several cam timers, solenoid valves, and automatic needle valves.

$$\sqrt{\frac{C}{\text{Rate}}} = \frac{KC}{\sqrt{k}} + \frac{1}{\sqrt{k}} \qquad (4)$$

By assuming the Arrhenius form of the rate constants, and determining their values at several temperatures, the activation energies can be deduced. Results for platinum, shown in Fig. 5, are in excellent agreement with current literature data.

INTERPHASE GRADIENTS

Concentration and temperature gradients between the catalytic surface and the bulk gas phase depend upon two parameters as defined by

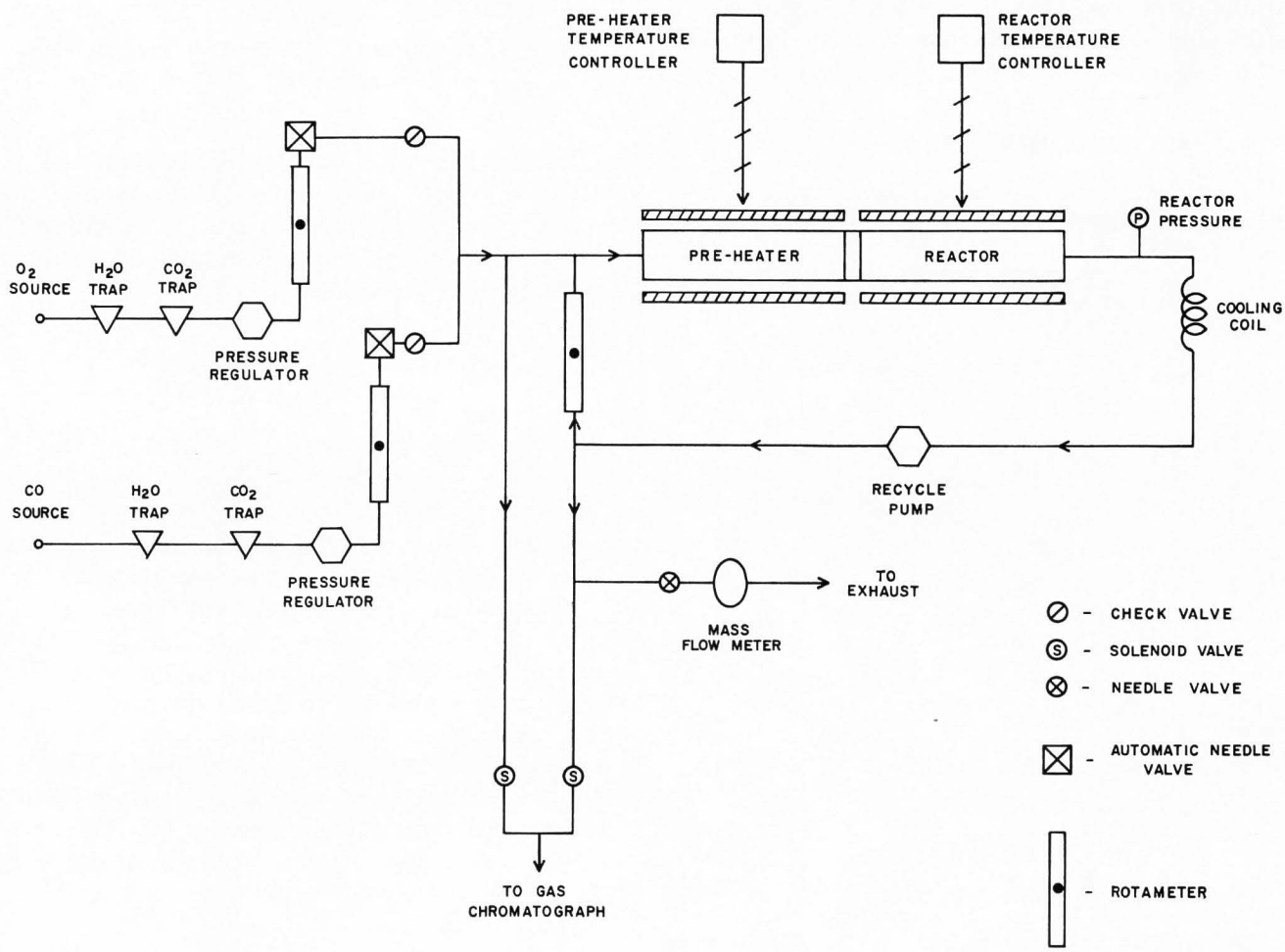


FIGURE 3: Details of Notre Dame automated recycle reactor system.

Carberry (5):

$$\eta Da = \frac{Rate}{k_g a C}$$

$$\bar{\beta} = \frac{-\Delta HC}{\rho C_p T Le^{2/3}}$$

where k_g is the external mass transfer coefficient, a is the surface to volume ratio of the catalyst pellet, ΔH is the enthalpy of reaction, T is the reaction temperature, Le is the Lewis number (usually one for gases), ρ is the gas density, C_p is the gas heat capacity, and C is the reactant concentration in the reactor (which is equal to the effluent reactant concentration at high values of R). Then, the dimensionless ratios of surface to bulk values are defined as:

$$\frac{C_s}{C} = 1 - \eta\, Da$$

$$\frac{T_s}{T} = 1 + \bar{\beta}\eta\, Da$$

Gradients of less than 1% will not significantly effect kinetic data. In this investigation, gradients were less than 0.2% for all operating conditions.

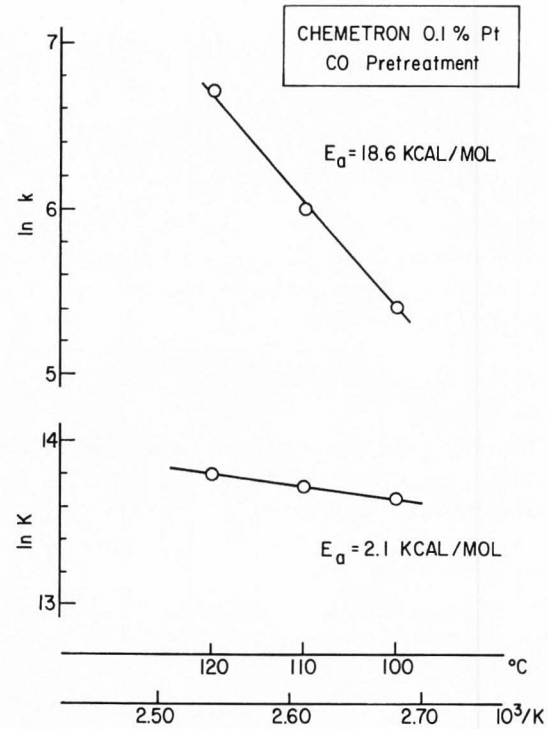


FIGURE 5: Plot of log k and log K vs. inverse temperature for supported platinum catalyst.

INTRAPHASE GRADIENTS

THE RIGOROUS EVALUATION of concentration and temperature profiles within a single catalyst particle involves the simultaneous solution of two coupled second order differential equations describing the heat and mass transport within the pellet. However, the maximum temperature difference between the center and surface of the pellet can be readily calculated (5):

$$\frac{\Delta T}{T} = \beta(1 - \eta\, Da)$$

where

$$\beta = \frac{-\Delta H\, DC}{\lambda T}$$

and D is the diffusivity of the reactant in the pellet, while λ is the pellet thermal conductivity.

This assumes that the reactant concentration is equal to zero at the pellet center, and is equal to $(1 - \eta\, Da)$ at the pellet surface. While the recycle reactor does nothing to eliminate this gradient, for small pellets, the internal temperature gradients are minimal. The gradients can be further limited, as in this investigation, by depositing active metal only on the external geometric surface of the pellet. The pellet center is then inert, and in the absence of reaction, remains near the surface temperature.

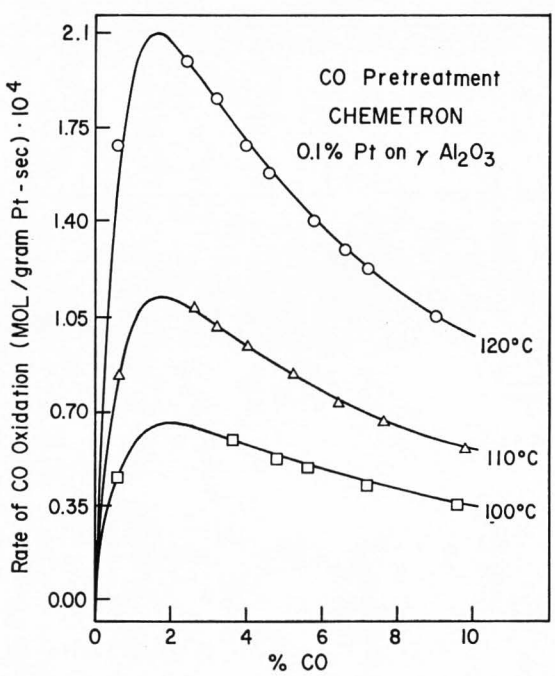
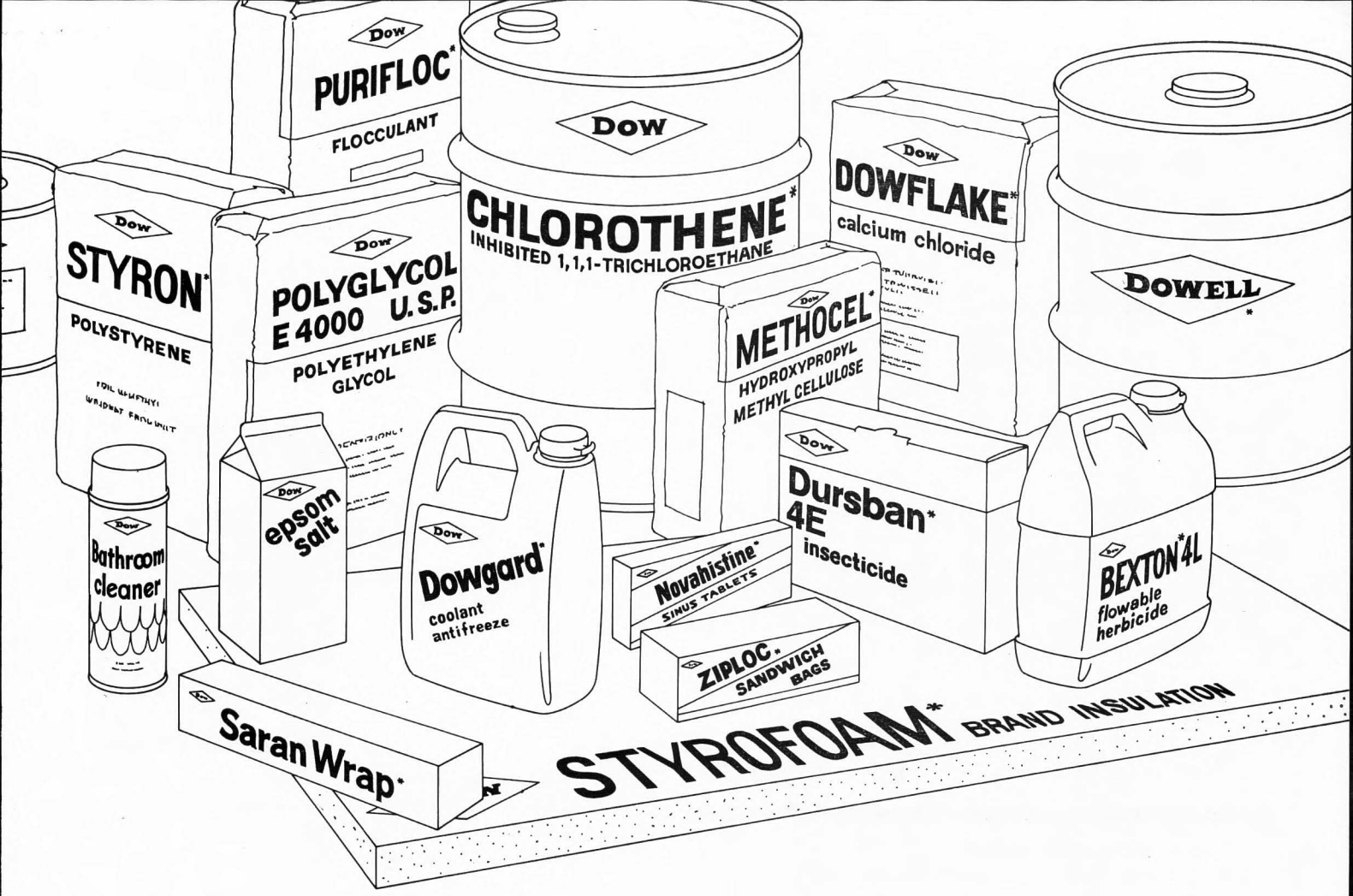


FIGURE 4: Plot of reaction rate vs. % CO for supported platinum catalyst.

Continued on page 100.



The people behind these products still remember looking for their first job.

They were people who wanted a good job with a good company. A chance to show what they could do. And to be recognized for doing it.

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WHAT IS CACHE?

By the
*TRUSTEES OF CACHE**

CACHE is a nonprofit organization whose purpose is to promote cooperation among universities, industry, and government in the development and distribution of computer related and/or technology based educational aids for the chemical engineering profession.

President of CACHE

David M. Himmelblau, University of Texas

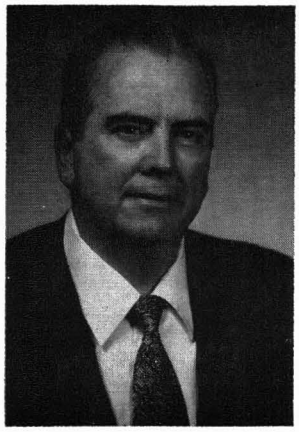
HOW DID CACHE GET STARTED?

IN THE 1960'S THE rapid growth of computer technology led to the development of many types of software packages that were quite useful in chemical engineering education. These packages in general were developed by university researchers, who welcomed the opportunity to explore a new computational method, but were less than enthusiastic about preparing and disseminating well-documented and debugged products. As a result, many programs which were developed at different sites were essentially not transferable. Even in those cases where well documented and debugged programs were prepared, most chemical engineering departments were not equipped for, nor disposed toward, maintaining program libraries on the digital computer and providing consultation services and program maintenance.

Even in those cases where well documented and debugged programs were prepared, most ChE departments were not equipped for . . . maintaining program libraries on the digital computer and providing consultation services and program maintenance.

This somewhat anarchistic state of development led Warren Seider and Bryce Carnahan to arrange a meeting of 14 chemical engineering educators in April of 1969. This meeting resulted in the formation of the CACHE (Computer Aids for Chemical Engineering Education) Committee.

After considerable discussion, it was decided that the principle goal of the Committee would be to "accelerate the integration of digital computation into the chemical engineering curriculum by inter-university cooperation in the preparation of recommendations for curriculum and course outlines, and the development of new computing systems." The purpose of the Committee was to encourage individuals at various universities to prepare software, to avoid duplication of effort, to achieve as much compatibility as possible, and to



Vice President of CACHE

Richard R. Hughes, University of Wisconsin:

*Submitted by D. M. Himmelblau, University of Texas, Austin, TX 78712.

. . . the principle goal of the Committee would be to "accelerate the integration of digital computation into the chemical engineering curriculum by inter-university cooperation in the preparation of recommendations for curriculum and courts out-lines, and the development of new computing systems."

adhere to standards for documentation and distribution.

During the next year and a half, the CACHE Committee organized several task forces to carry out specific activities. From 1971 to 1975 the CACHE Committee obtained sponsorship from the Commission on Higher Education of the National Academy of Engineering, and obtained funding from the National Science Foundation to support its work. In 1975, after several successful projects had been completed, CACHE was incorporated as a not-for-profit corporation to serve as the administrative umbrella for the consortium activities.

HOW IS CACHE ORGANIZED?

THE CORPORATION IS directed by up to 21 Trustees who are elected for three year terms. Nominations can be made by any of the chemical engineering departments in the United States and Canada. In addition to the Trustees, three representatives from industry serve as CACHE members, and an Advisory Committee has been organized composed of five distinguished academic representatives. The names of the current Trustees, Industrial members, and Advisory Committee members, together with their affiliations are listed in Table 1.

In addition, each department of chemical engineering in the United States and Canada has a local CACHE representative (approximately 150 in all), and 21 representatives have been appointed in 12 other countries throughout the world. These representatives serve as the focal point for communication with CACHE. They also provide feedback to CACHE on the needs of their departments.

CACHE activities are carried out by task forces organized to accomplish specific objectives. The chairman of each task force is a Trustee of the CACHE corporation, but members of the task force typically include other engineering educators and representatives from industry. The Trustees of the CACHE corporation meet twice yearly for three days to coordinate task force activities. All participants in the task forces are volunteers who might (or might not) otherwise work alone. For special projects, such as writing a module or editing a volume of computer codes, very modest fees have been paid if funds are provided by the agency providing the financial support for the Task Force.

WHAT HAS CACHE ACCOMPLISHED?

Some of the major activities of CACHE are as follows:

Standards for computer programs. CACHE developed and published mechanisms for standardization of computer programs, system conventions,

TABLE 1

Trustees of Cache

D. M. Himmelblau, Pres.	Univ. of Texas at Austin
Richard R. Hughes, V-Pres.	Univ. of Wisconsin
Richard S. H. Mah, Sec.	Northwestern Univ.
Lawrence B. Evans, Treas.	M.I.T.
Brice Carnahan	Univ. of Michigan
Thomas F. Edgar	Univ. of Texas at Austin
Scott Fogler	Univ. of Michigan
Ernest J. Henley	Univ. of Houston
Duncan A. Mellichamp	U. of Calif. (S. Barbara)
Rodolphe L. Motard	Washington Univ.
G. V. Reklaitis	Purdue Univ.
J. D. Seader	Univ. of Utah
Warren D. Seider	Univ. of Pennsylvania
George Stephanopoulos	Univ. of Minnesota
Arthur W. Westerberg	Carnegie-Mellon Univ.
James W. White	Univ. of Arizona
Joseph D. Wright	McMaster Univ.

Industrial Members

Theodore L. Leininger	E. I. duPont de Nemours & Co.
Edward M. Rosen	Monsanto Company
Louis J. Tichacek	Shell Oil Company

Advisory Committee

William H. Corcoran	California Inst. of Tech.
James R. Fair	U. of Texas
Donald L. Katz	Univ. of Michigan
W. Robert Marshall	Univ. of Wisconsin
John J. McKetta	Univ. of Texas at Austin

CACHE developed and published mechanizations for standardization of computer programs, system conventions, documentation and terminology so as to facilitate inter-university exchange of computer-based instructional materials.

documentation, and terminology so as to facilitate inter-university exchange of computer-based instructional materials. Standards were established for programming, documenting and testing self-standing computer programs and subprograms.

Computer programs for core chemical engineering courses. From 1971-73, under the direction of Ernest J. Henley, 125 computer programs were published for use in seven core chemical engineering courses, namely stoichiometry, kinetics, control, transport phenomena, thermodynamics, design, and stagewise computations. These programs, written by approximately 100 professors, were small, containing approximately 50-500 statements. Most solved particular problems in a course typical of programming assignments for homework. The programs are now in their fourth printing.

Physical property data bases (information systems). CACHE has promoted the exchange of information on the design and implementation of academic and industrial physical property information systems. We are presently negotiating to purchase PPDS, a physical properties package that can be placed on a network and shared by all chemical engineering departments.

Modular instructional materials for core chemical engineering courses. A complete set of 250 modules has been prepared for six core chemical engineering courses. Each module represents roughly one lecture in a conventional course and contains, in addition, study questions and homework problems. The seven curriculum areas are control, transport, stagewise processes, material and energy balances, kinetics, and thermodynamics. This project has been supported by the National Science Foundation. Publication of the modules is being initiated by the AIChE.

Real time computing. To promote the introduction of real-time computing material into the undergraduate curriculum, CACHE conducted workshops on real-time computing, prepared course outlines, developed standards for real-time computing programs, developed and compiled fully documented prototype experiments, and has published a set of introductory monographs on the subject.

FLOWTRAN for educational use. CACHE with the help of the Monsanto Company has made FLOWTRAN available on a national network for use by students. As members of the Large Scale Systems Task Force considered methods to share subsystems, it became clear that industrial systems, such as Monsanto's FLOWTRAN, which was one of the best available commercial chemical process simulation and design programs, offered (1) a more complete collection of subsystems to permit solution of more practical problems, and (2) well-tested and maintained software. Furthermore, computer networks permitted installation of this proprietary program on a single computer for use at remote sites throughout the United States.

Since 1974, 45 different schools have used FLOWTRAN on UCS. Table 2 shows that the number of schools spending over $100 per year has leveled at approximately 24, whereas total usage is climbing, but the average expenditure per school (excluding schools that expend over $3,000 per year, a usage presumed to reflect graduate research rather than teaching) is decreasing. We believe that most schools expending less than $3,000 per year are using FLOWTRAN for coursework; on this basis, and assuming 20 students per school (in a senior design course), the average cost per student is decreasing slowly.

TABLE 2
Summary of FLOWTRAN Usage

	1974-75	1975-76	1976-77	1977-78
No. of Schools*	18	24	23	25
Annual Amount Spent	$15,700	$21,700	$31,900	$36,800
Avg. per School†	$870	$765	$710	$670
Approx. No. of Students	360	480	460	500
Avg. Cost per Student	$43	$38	$34	$33
Book Sales	900	400	870	

*That spent over $100/yr.
†Excluding schools that spent over $3,000/yr.

Three publications related to the use of FLOWTRAN have been published, and over 2000 volumes of "FLOWTRAN Simulation" by Seader and Pauls have been sold.

Computer Graphics. Surveys and a study of available software and hardware have been completed and published.

Continued on page 98.

USING TROUBLE SHOOTING PROBLEMS*

Edited by
DONALD R. WOODS
McMaster University
Hamilton, Ontario, Canada

Professional engineers must be good at solving a variety of problems. A type of problem that professionals encounter often is the trouble shooting or diagnostic problem. In such problems, an unexpected difficulty has arisen; something is wrong that must be corrected immediately, safely, and with a minimum of cost. Here is an example: "For the past 10 minutes the product has been off-specification; get this corrected because we are losing $2000 for every hour we produce this unsaleable product!" The problem can be caused by technical mistakes, people mistakes, or misunderstandings. The data required to solve the problem usually have to be collected. This type of problem can provide a very effective vehicle for motivating students and improving their skill at solving problems. It can be used to train undergraduates, graduates, and professionals in industry. Some examples of how these trouble shooting problems can be used have been given previously [1, 2, 3, 4]. The purpose of this article is to extend the ideas presented in those early articles and to illustrate the variety of approaches that can be used.

TROUBLE-SHOOTING AT CANADIAN INDUSTRIES LIMITED

WILLIAM K. TAYLOR
Canadian Industries Ltd.
Courtright, Ontario, Canada

The following comments describe not how trouble-shooting cases are used as a training aid, but how trouble-shooting in general fits into an industrial environment and how an engineer can take advantage of the problem solving opportunities facing him. Some ground rules are then offered that hopefully will aid readers in avoiding some of the common pitfalls of problem solving. The comments pertain to a heavy industrial site consisting of several chemical plants of different types.

The trouble-shooting technique has been described elsewhere and we will not go into detail here. Basically, it can be described as the use of the scientific method and sound engineering principles to solve problems. The four basic steps in the problem solving process are:

1. **Realize something is wrong.**
2. **Define the problem; collect data.**
3. **Make conclusions; evaluate possible solutions.**
4. **Implement the solution.**

TYPES OF PROBLEMS ENCOUNTERED

In heavy industry, problems can arise at several levels of sophistication ranging from simple mechanical failures to innovative debottlenecking studies. The same trouble-shooting techniques can be used over this whole range of problem solving activities.

At the basic level, problems will be encountered with operating plants and Step #1 in the above-mentioned method will be quite easy: the product is off-spec., a pump does not work, production rate or efficiency is below normal, etc. You do not need anyone to tell you something is wrong; it is quite obvious. The fault, however, may not be so easy to find. It may be easy to determine what is wrong with a pump, but, diagnosing that a heat exchanger has an internal leak might be considerably more difficult. These trouble-shooting problems are

*This is the first installment of a two-part series. The second installment will appear in the Summer 1980 issue of *CEE*.

D. R. Woods is a graduate of Queen's University and the UUniversity of Wisconsin (Ph.D.). For the past three years he has been attending all undergraduate lectures along with the students to try to discover what needs to be done to improve student's problem solving skills. His teaching and research interests are in process analysis, and synthesis communication skills, cost estimation, separations, surface phenomena and developing problem solving skills. He is the author of "Financial Decision-Making in the Process Industry." He received the Ontario Confederation of University Faculty Association award for Outstanding Contribution to University Teaching.

generally handled by plant operating personnel but in some cases they may need help. The engineer, whatever his responsibilities, should make an effort to get involved in these problems. He will gain valuable experience in dealing with practical problems, and even if he is not directly involved he should assure himself that the proper trouble-shooting procedures are being followed. Because Step #1 is "given", this is also the type of problem that can be used in the case study/classroom method of instruction.

At the next level of sophistication the term trouble-shooting gives way to the more general term problem solving. Also, Step #1, the realization that something is wrong, is by no means obvious.

At this level, looking for and finding problems is the key and the engineer should play a dominant role. Plant operating personnel are generally very familiar with their equipment, its operating characteristics and limitations. They will operate their equipment to the best of their and the equipment's ability. They will come up with ideas to improve things, but they are not plant designers and may not recognize design errors. An example of this type of problem is a high pressure drop in piping system that limits the output of a pump or compressor. As far as the plant operator is concerned, it is not a problem as long as it works. The engineer, however, should be able to recognize this as a problem (Step #1) and then collect data, check the calculations, design data, etc., before reaching a conclusion. This type of problem will command attention when production is limited (the squeaky wheel gets the grease syndrome) but otherwise just how many similar problems are waiting to be discovered? Another type of example in this category is that of equipment and instrumentation systems that are too complicated to do a simple job; the result can be poor operations and a lot of effort expended to make something work when the real solution is to simplify the installation and eliminate unnecessary equipment (provided, of course, that safety and reliability standards are maintained). Clearly the ability to recognize, as well as solve, problems is a key asset for any engineer. The techniques for finding problems are similar to those used for solving them. By asking the right questions (of himself, the plant designers, the plant operators, etc.) and by remaining somewhat of a skeptic the engineer is sure to uncover problem areas. In the development of a new engineer, the ability to recognize problems can often be a key turning point.

We are now overlapping into the next level of problem solving; that is optimization, de-bottlenecking and even innovation. The same techniques apply as for basic trouble-shooting. At this level the problem definition (Step # 2) and evaluation of alternatives (Step # 3) will require substantial engineering input. In the past few years, as energy costs have soared, opportunities have arisen to make existing plants more efficient. In a general sense this can be considered a problem solving activity. Many of the solutions to optimization, de-bottlenecking, and energy-related problems are considered innovative but they are really just the result of a lot of hard work and are a logical extension of the application of trouble-shooting techniques.

To summarize, demonstrated problem solving

The engineer, whatever his responsibilities, should make an effort to get involved in these problems. He will gain valuable experience in dealing with practical problems, and even if he is not directly involved he should assure himself that the proper trouble-shooting procedures are being followed.

A major source of trouble-shooting problems should be our industrial colleagues. This is true especially now, when many, if not most, faculty members have had little or no industrial experience.

ability is a valuable asset for any engineer. The ability to recognize and solve problems is the key to a successful career for many engineers and the engineer who is good at solving problems is also likely to be considered an innovative engineer.

GROUNDRULES FOR TROUBLE-SHOOTING

The following is offered as a partial list of guidelines in order to avoid some of the common pitfalls of trouble-shooting.

1. It goes without saying that there is no substitute for a knowledge of fundamentals, whether it be fluid flow, process control, distillation theory, etc.
2. Similarly, there is no substitute for knowledge of the process/plant/equipment/etc. having the problem.
3. When defining a problem (Step #2), do not confuse someone's interpretation of what is wrong with the observations. Human nature being what it is, people will tend to give their theories or conclusions as to what is wrong, instead of reporting observations. Perhaps they are right but their conclusions may not be supported by the facts. A common mistake is to jump to a conclusion that a particular thing is at fault because this is a common type of failure. Many, or most, people are guilty of these tendencies, including engineers.
4. While working on a problem an engineer may want to collect plant data, conduct test runs, have samples analyzed, etc. It is important that the engineer collect the data himself, be present when the data is collected, or otherwise assure himself that the job is being done properly.

Many needless hours have been wasted on poor data resulting from uncalibrated plant instruments, mislabelled sample bottles, missed readings, etc.

When relying on non-routine lab tests the engineer should have an understanding of the analytical techniques used and whether or not they will tell him what he wants to know. Accuracy and reproducibility of the tests should be known. If the lab technique is dependent on the use of known standards then the number, age, condition and range of the standards should be known. If you are analyzing for 2% component x and the only standard contains 50% component x then all the results may be meaningless. It has also been known for standards to be wrong and using two or three standards can eliminate this possibility.

5. Be aware of any assumptions you make when solving problems. Be prepared to re-examine assumptions and to discard them when necessary.

TROUBLE-SHOOTING AT THE UNIVERSITY OF WISCONSIN

CHARLES C. WATSON
University of Wisconsin
Madison, WI

We have used a few trouble-shooting problems; however our main emphasis has been on the more structured and synthesis type of problem, in the form of developing a reasonably near optimum design to fit a given need. From our experience here are some thoughts about the advantages and disadvantages of using trouble shooting problems.

Advantages

1. Student introduction to the type of situation he (or she) will meet in pilot plant operation, production, sales and service, etc. (most students confess they have no idea how what they are learning will translate into professional life. Only a few of our students will graduate with adequate industrial summer work experience, to judge from recent observations.)
2. Experience gained in the sort of practical reasoning which is important in industrial work. Standard theory courses can afford neither the time for this nor the distraction from the orderly development of theoretical principles which such problems would entail.
3. Showing the student, by actual demonstration, that there may be more than one way to reason through a problem.

Disadvantages and precautions

1. Some trouble-shooting problems are such that it is not reasonable to expect inexperienced

people to reason from effect to cause. There may even be more than one chain of events which would lead to the observed effect, or effects, so the cause cannot really be determined. Even an experienced engineer can be misled.

2. Supposing that we devise problems with an unique and correct result from such backward reasoning, there is danger in tempting the unwary student to generalize, and to believe this will always be the case with real life problems. The keen student is going to be suspicious of what seems to him (or her) a cooked-up problem, and will wonder if such exercises really lead to practical proficiency.

The above difficulties can, of course, be handled by careful presentation and adequate discussion and summing-up by the instructor; they can be made to contribute to the practical instruction of the students, particularly if they are given an adequate role in these discussions and allowed a measure of discovery of the character of trouble-shooting problems. But the problems used have to be either real ones, or very carefully thought-through synthetic ones.

A major source of trouble-shooting problems should be our industrial colleagues. This is true especially now, when many, if not most, faculty members have had little or no industrial experience. Of course, good consulting experience can provide problems, too.

Trouble-shooting may well be approached more efficiently by applying some rational analysis, when time permits. One may thus be more successful, especially when there is a complex chain of consequences from an original fault in a system, with secondary faults, etc. Applications of fault-free analysis, as is done in raliability studies, might even be programmed for computer solution so that a large number of failure patterns can be examined. Observations which indicate potential trouble, or which follow actual system failure, could then be matched to the analyses and the probable cause inferred. Dale Rudd and his students have done fruitful work in this area [6, 7]. Long ago, we concluded that there was a structure to disaster, which behooves the engineer to study carefully.

We are now overlapping into the next level of problem solving; that is optimization, de-bottlenecking and even innovation.

TROUBLE SHOOTING CASES AT McMASTER HEALTH SCIENCES

HOWARD S. BARROWS,
VICTOR R. NEUFELD,
J. W. FREIGHTER AND
GEOFF R. NORMAN
Dept. of Medicine
McMaster University
Hamilton, Ontario, Canada

In the Faculty of Health Sciences, we have centred our educational program around the biomedical or health care problem. Our conviction is that the students learn best when *they* choose what they need to learn. The problem is in the vehicle for learning. These problems are encountered in the regular work of a Medical Doctor, and so it is natural that our emphasis is on this type of problem. Primarily we use one format: small groups of five students together with a tutor identify the issues in any problem, discover what they need to know, learn that information through self study, determine the underlying mechanisms and propose short and long term corrective actions. The structure of these problems is modelled on extensive research done on the diagnostic process in medicine.

The problems . . . provide opportunities for the students to learn the necessary background knowledge to function successfully as an M.D.

The distinctive characteristics of our approach are:

1. Students obtain information on their own and share it with other student members in the group,
2. The tutor's role is supportive and aimed at developing productive group and problem solving skills,
3. The students prepare their own objectives and questions they wish to explore, within the general framework for a particular 10-week unit,
4. The student is guided through the stages of cues-hypothesis-inquiry strategy and decisions as well as through the self directed studies.

The problems are carefully selected to provide opportunities for the students to learn the necessary background knowledge to function successfully as an M.D.

What format is used for the problem state-

ment? We use at least two major formats (the box problem, and the paper case protocol) with enrichment available through simulated patients, and the P4 card deck computer simulations. The problem box provides the student with the initial problem statement, and a self-paced set of key questions relating to the topics to explore. The box may include pertinent slides, audio tape of an M.D. interviewing the patient, X-rays and laboratory test result sheets. This additional information will be needed as the students work through the problem. In the simulated patient format, a well-trained, healthy patient portrays an actual patient with a given illness and can thus respond to the students with appropriate answers and systems.

In the computer simulation format, various systems of the body are simulated on the digital computer. Faults with the system are programmed in and the student is expected to discover the faults by asking the right questions and interpreting the output data. This approach is similar to that used by Doig [5]; however, here we are dealing with a simulation of a medical system.

In the P4 card format, the student is given a deck of cards, based on an actual patient problem, from which he selects the card most likely to him to identify the fault and prescribe a cure. An initial card poses the problem. He may select from about 50 "questions I must ask the patient". Each card asks the student to state to himself where this question (or card) fits into the problem definition, the hypotheses he is developing, and the information he needs. On the back of each card is the answer to the question. Another possible set of cards provides the answers to examination tests the students might wish to do. This set provides about 25 alternatives.

The student may choose from about 30 laboratory tests he might want done or he may choose to bring in one of 20 different expert consultants. From the student's selection of cards from these four sources of information he should be able to identify the fault. He then chooses one of our forty medications or patient care prescriptions. The exercise is completed by means of a closure card. Experienced diagnosticians have made their choice of cards and the "good" choices are coded so that the student receives instant feedback as to the quality of his choice: +2 if his choice coincides with that of the expert and –2 if he makes a poor choice. A problem box and P4 deck have been developed for this type of problem. The Problem Box consists of charts, photograph, x-rays, and written data. The P4 deck consists of five different sets of cards from which the problem solver can select those that he/she feels are pertinent. More details of the complete program are described elsewhere [8, 9, 10].

We have an initial set of 15 (problems) . . . Now our former students send us sufficient industrial problems each year to supply new situations and challenges for subsequent classes

TROUBLE SHOOTING AT McMASTER

DONALD R. WOODS
McMaster University
Hamilton, Ontario, Canada

At McMaster three different formats have been used:

1. Students work on their own to determine the cause, and pose short and long term corrective action.
2. Students work as a group to determine the cause, and pose short and long term corrective action.
3. Students work on own to outline cause finding strategy.

The first two formats are similar and will be the main emphasis described here. The third format is used on examinations and is similar to that used at the University of Waterloo [3, 4].

The distinctive characteristics of our approach are:

1. Students obtain information from the instructor by asking questions about past experience, results of calculations, and results of experiments that the student wants performed.
2. Students do not do any calculations.
3. Students are charged a cost related to the downtime and direct costs incurred because of their questions.
4. The "best" solution is that where the problem is solved with the minimum total cost.
5. Students are not limited in the types of questions they can ask.

With the individual format the students write down the question they want answered or experiment they want performed, raise their hand and

Continued on page 96.

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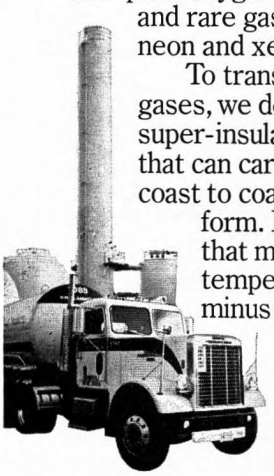

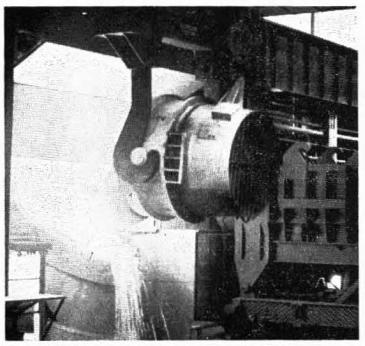

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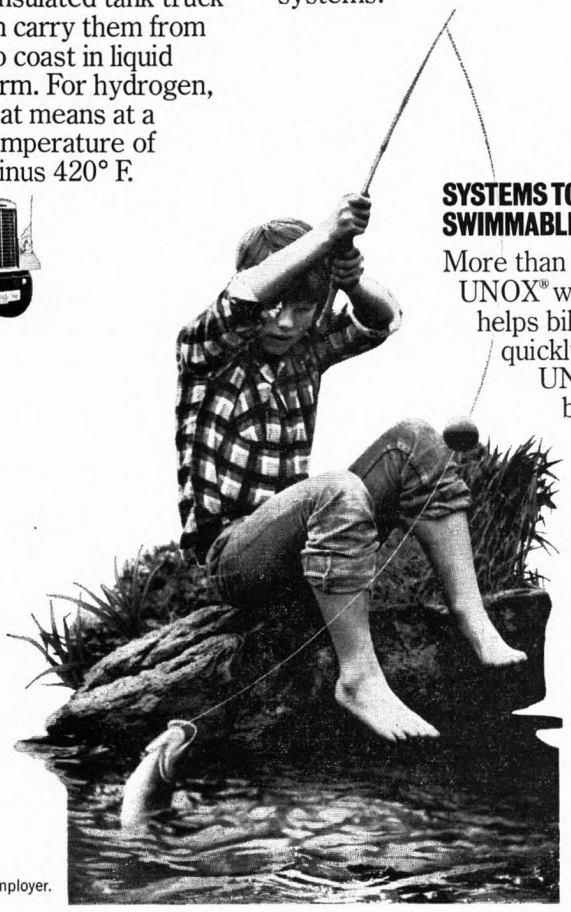

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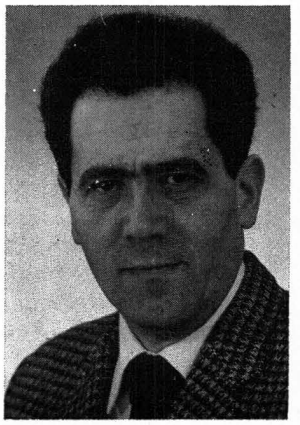
A New Venture in Graduate Education:
CO-OP PH.D. PROGRAMME IN CHEMICAL ENGINEERING

THOMAS Z. FAHIDY
University of Waterloo
Waterloo, Ontario N2L 3G1 Canada



Thomas Z. Fahidy received his B.Sc. (1959) and M.Sc. (1961) at Queen's University (Kingston, Ontario) and Ph.D. (1965) at the University of Illinois (Champaign-Urbana) in chemical engineering. He is Professor and Associate Chairman of Graduate Studies in the Department of Chemical Engineering, University of Waterloo (Canada) where he teaches courses mostly in applied mathematics to engineering students and conducts research in electrochemical engineering. His major research areas are magnetolectrolysis and the development of novel electrochemical reactors, where he is the author of numerous scientific articles. Fellow of the Chemical Institute of Canada and one of the (two) associate editors of the Canadian Journal of Chemical Engineering, he is also a member of a number of professional associations and a registered Professional Engineer in the province of Ontario.

SINCE WE INTRODUCED ourselves to *CEE* readers some years ago [1], our cooperative system has continued to enjoy unperturbed growth. While ten years ago several hundred industrial and governmental employers participated in the co-op scheme of undergraduate education, this year their total number is about 5,000, and about 1,800 are employers of engineering students. With roughly one-half of our student population (6,600) in the co-op programme, Waterloo is now the second largest fully cooperative engineering school in North America and the largest in Canada, where Sherbrooke, Memorial, Regina and Victoria also have cooperative arrangements.

Much of this success is due to the efforts of our Coordination Department which is engaged full-time in arranging recruiting interviews and in looking after students on their work terms; there are twelve full-time engineering coordinators (all graduate engineers) devoted entirely to the engineering contingent of the programme. They are very busy.

The graduate arm of engineering education at Waterloo has grown essentially in a classical pattern and the "full-time-research-on-campus" scheme has been predominant especially in the Ph.D. programme, whose normal maximum duration past the M.A.Sc. degree is four years. While special arrangements may be made for part-time and off-campus Ph.D. studies, the advantages of the cooperative scheme, amply documented on the undergraduate level, have not yet been explored sufficiently in our post-graduate education. The co-op Ph.D. programme is, in our opinion, the first significant step in this direction with two major goals in mind:

- **To enable participating students to attain important practical experience, discipline and organizational ability in an industrial environment during the external period and to prepare for a comprehensive effort on their chosen research topic.**
- **To provide participating employers (industrial and governmental) with an enhanced opportunity to become acquainted with the qualifications and the scholarship of Ph.D. candidates.**

The structure of the Co-op Ph.D. programme is shown in Table 1. Canadian citizens and landed immigrants who possess a Bachelor's degree in Chemical Engineering from a recognized university and have a minimum average final grade of 78% are admissible; the grade minimum is five per cent higher than the minimum requirement for the standard Ph.D. programme and the citizenship/immigration status is required by current government regulations of financial support and employment conditions. Each application is individually evaluated by the Associate Chairman of Graduate Studies and the departmental Graduate Review Committee before recommendation is formally made to the Associate Dean of Graduate Studies of the engineering faculty. The minimum average grade obtained in graduate courses taken in the programme must

TABLE 1
Structural Characteristics of the Co-op Ph.D. Scheme

PHASE AND DURATION	FUNCTION	FINANCIAL ASPECTS	REMARKS
1. Preparatory; two consecutive terms	Six graduate courses. Teaching Assistantship duties. Interviews with prospective employers for employment in the second phase.	Teaching assistantships, departmental bursaries and external scholarships	Entry in any of the Winter, Spring and Fall terms. Strict admission requirements. High minimum course average to be maintained.
2. Industrial; three consecutive terms	Practical (research) experience in a nonacademic environment. Preparation of a comprehensive work report describing the off-campus professional activities.	Market-level salaries.	Employment obtained via services of the Co-ordination Department.
3. Research; minimum two years	Two graduate courses. On-campus research project. Comprehensive oral examination. Submission of Ph.D. thesis and oral defence.	As in phase 1.	High minimum course average and high quality of research performance to be maintained.

be 75% at any given time (also five per cent higher than the minimum requirement in the standard Ph.D. programme) ; this is a prime condition for maintaining a candidate's satisfactory status, apart from specific conditions pertaining to each of the three phases.

The work period and the work report form a crucial component of the programme. In the industrial phase candidates acquire not only material and disciplinal experience in industry but they are also expected to derive special skills and motivation which will enable them to carry out original and high-quality research in the third phase. The work report should demonstrate to the employer a candidate's ability to do lucid and concise technical writing, and it should also serve as a "mini-rehearsal" for the research thesis. Higher than normal intramural earnings in the work period constitute the pecuniary benefits of the second phase.

The research phase resembles to a large extent its counterpart of the standard Ph.D. programme. The thesis topic is chosen via consulting with an officially appointed faculty supervisor who will advise and direct the candidate throughout the research project. The comprehensive oral examination of the proposal by a faculty-appointed committee is to be passed not later than six months after return to campus and the oral thesis defence is to be passed upon submission of the doctoral thesis.

There is no Master's degree in this scheme; it leads directly to the Doctor's degree. We feel that this feature is attractive to those who are determined to seek the highest degree of formal education while defying the risks of a shorter unconventional path.

We at Waterloo believe that this scheme is a rewarding challenge to highly mature and self-disciplined students by offering, apart from the technical knowledge and aptitudes accumulated in both academic and off-campus periods, a wider perspective of the chemical engineering profession and of personal career development. One additional benefit that may accrue from the enhanced mutual awareness and cooperation between the University and employers of chemical engineers, which this effort necessitates, is the emergence of Ph.D. thesis topics with an academically respectable and yet industrially practicable substance.

A flyer and further details of the programme are available from the Department of Chemical Engineering, University of Waterloo.

REFERENCES

1. M. Moo-Young, "Ch.E. Department: Waterloo", Chem. Engrg. Educ. IX (5), 4 (1975).

TROUBLE SHOOTING PROBLEMS

Continued from page 92.

receive a written answer immediately from the instructor. With the group format, the students choose a chairman whose role is to focus discussion on what question they want answered and forward the question through to the instructor for his response. About one tutor or instructor is required in the room for every ten students.

What problems do we use? We have an initial set of about 15 that we developed from our industrial experience. Now our former students send us sufficient industrial problems each year to supply new situations and challenges for subsequent classes. A set of such problems is available. We are currently exploring the appropriateness of running these sessions at the plant in a local industry, using problems they encountered and interacting with plant personnel.

The advantages of this approach are that the students begin to appreciate the cost implications of their decisions, and they can ask any question they like. There are two extreme approaches to solving these problems: the Kepner Tregoe approach (where the focus is on discovering when in time some change was made to cause the fault [11, 12, 13] and the hypothesis generation approach where all the current evidence is analyzed, alternative causes are created and most likely alternatives are tested. This format allows the student to use either method or a combination of these methods to solve the problem.

The main difficulties the students have are that they cannot accurately estimate the time required (and hence the cost) to answer some of their questions, they usually are not very organized in their approach to solving this type of problem, and they rely almost entirely on the hypothesis generation approach. To overcome some of these difficulties we have listed time and cost estimates for many commonly performed analyses, experiments or equipment modifications. To try to discover how to improve their approach to solve problems we have started a separate project. Details of this approach are available elsewhere [14, 15]. □

REFERENCES

1. Woods, D. R. (1966). "Complement to Design: Trouble-Shooting Problems." Chem. Eng. Education. Jan. p. 19-23.
   Woods, D. R. (1968). "Trouble-Shooting Problems: Problem Specifications" and (1973) Teacher's Guide. McMaster University, Hamilton.
2. Woods, D. R. (1967). "The Use of Short Trouble Shooting Problems." Chapt. 3 in "Chemical Engineering Case Problems," C. J. King, editor. AIChE. New York.
3. Silveston, P. L. (1967). "Trouble Shooting Problems as Teaching Aids." Chapt. 4 in "Chemical Engineering Case Problems," C. J. King, editor. AIChE, New York.
4. Silveston, P. L. and Woods, D. R. (1966). "Use of Trouble-Shooting Problems in Undergraduate Chemical Engineering Design Courses." Paper presented at the CSChE Conference, Windsor, Ont. Oct. 19.
5. Doig, I. D. (1977). "Training of Process Plant Malfunction Analysts." Chemeca 77, Canberra, 14-16 Sept. p. 144-148.
6. Rivas, J. B., Rudd, D. F. and Kelly, L. R. (1974). "Computer-aided Safety Interlock Systems," AIChE Journal *20*, No. 2, p. 311.
7. Rivas, J. R. and Rudd, D. F. (1974). "Synthesis of Failure-Safe Operations." AIChE Journal *20*, No. 2, p. 320.
8. Barrows, H. S. and Tamblyn, R. (1977). "Guide to the Development of Skills in Problem Based Learning and Clinical (diagnostic) Reasoning." 53 p. Monograph NA.1., McMaster University, Faculty of Health Sciences, Hamilton.
9. Barrows, H. S. and Bennett, K. S. (1972). "The Diagnostic (Problem Solving) Skill of the Neurologist." Archives of Neurology *26*, p. 273-277. March.
10. Neufeld, V. R. and Barrows, H. S. (1974). "The 'McMaster Philosophy': An Approach to Medical Education." J. Medical Education *49*, p. 1040-1050.
11. Kepner, C. H. and Tregoe, B. B. (1965). "The Rational Manager." McGraw-Hill.
12. Kepner, C. H. and Tregoe, B. B. (1973). "Genco II." Kepner-Tregoe Inc., Princeton, N.J.
13. Kepner, C. H. and Tregoe, B. B. (1973). "Problem Analysis and Decision Making." Kepner-Tregoe Inc.,
14. Woods, D. R., Crowe, C. M., Hoffman, T. W. and Wright, J. D. (1977). "What is the Problem in Teaching Problem Solving?" To appear in the ASEE monograph on Problem Solving.
15. Woods, D. R., Crowe, C. M., Hoffman, T. W. and Wright, J. D., (1978). "56 Challenges to Teaching Problem Solving." McMaster University, Hamilton.

ChE book reviews

CHEMICAL AND ENGINEERING THERMODYNAMICS

By Stanley I. Sandler
John Wiley & Sons, N.Y.
Reviewed by C. M. Thatcher
University of Arkansas

Prof. Sandler sets forth two specific objectives in the preface to his book. The first is to provide a modern textbook, particularly relevant to other courses in the curriculum, for an undergraduate course in chemical engineering thermodynamics. The first part of this objective, at least, has been

met in a most commendable fashion: The subject matter is up-to-date and the coverage is impressively thorough.

The desired relevance is also evident, though subject to one's own interpretation of relevance at the undergraduate level. Specifically, the text includes two appendices which treat pertinent principles from the microscopic viewpoint encountered in transport phenomena. It also presents the familiar balance equations in time-derivative form. And, finally, it relates thermodynamics to reaction kinetics and mass transfer to a somewhat greater degree than do most other, similar texts already on the market.

This leaves the question of the text's suitability for undergraduate use and of Prof. Sandler's stated objectives pertinent thereto: To organize and present the material in such a way that the student might obtain both a good understanding of principles, and proficiency in applying these principles to the solution of practical problems. Hopefully, he meant to imply the book's use by a competent instructor to achieve this objective. The typical undergraduate student would not get very far by self-study alone.

The first five chapters take up the thermodynamics of pure fluids. The material is well-organized, and includes numerous example problems. However, a few familiar topics—such as the Rankine cycle and turbine efficiency—appear only in end-of-chapter problems. Perhaps this exemplifies the statement that "Steady-state processes are of only minor interest in this book." The prevalence of such processes in industry makes this statement really surprising in a text which claims relevance as an objective.

It is the remaining four chapters, devoted to the thermodynamics of multi-component systems, which perhaps reveal Prof. Sandler's primary interest and orientation. Here, one finds extensive theoretical discussion and mathematical derivation, with but few of the illustrative problems which characterize Chaps. 1 through 5. For example, fugacity is first introduced on page 337, and an f/P plot appears on page 349; but the first of only two illustrative problems involving fugacity is on page 375. It is also noteworthy that most of the end-of-chapter problems for Chaps. 6 and 7 are of the "prove," "derive," or "show that" variety. Practical application is largely deferred to the Chap. 8 and 9 problems.

The order of theoretical development has interesting consequences with respect to some topics which are conventionally treated as being closely related. Henry's Law, for example, is introduced in Chap. 6, while Raoult's Law first appears in Chap. 7. Similarly, heat of reaction calculations, developed in Chap. 6, are finally applied to adiabatic reaction temperature problems in the concluding pages of Chap. 9. The only end-of-chapter problems involving heat of reaction are also to be found in Chap. 9, not in Chap. 6.

A few additional, specific observations may be of interest. (1) The existence of SI units is acknowledged initially but then essentially ignored thereafter. (2) Tables and charts are scattered throughout the book, making them hard to locate for reference purposes. (3) The extensive use of functional notation—e.g., H(T,P) vs simply H—tends to obscure the significance of relationships in which it appears. (4) Computer algorithms might have been offered for some practical applications—e.g., flash vaporization—which, instead, are dismissed with little or no consideration because the calculations are "quite tedious."

In summary, the text is not just a new version of the conventional approach to chemical engineering thermodynamics. It is distinctly different, and gives one considerable insight into the particular approach favored by its author—i.e., emphasis on rigorous theoretical development. Among those who espouse the same approach, the book may well be hailed as a long-awaited solution to the textbook problem. Only their post-use reactions, and those of their students, can establish the extent to which Prof. Sandler has actually achieved his stated objectives.

Unfortunately, there seems to be little consensus among thermodynamics instructors regarding the approach—and therefore the text—which is most likely to produce optimum levels of student understanding and proficiency. It follows that Prof. Sandler's text is not likely to be widely adopted by those who strongly prefer a more pragmatic approach to thermodynamics, nor will it prove wholly suitable to all who may adopt it, with reservations, on a trial basis.

Prof. Sandler should be prepared for the distinct possibility of disappointment if he was seeking popularity as evidenced by widespread adoption. One suspects, though, that he sought instead to write a good book to meet the needs of those, however many or few they be, who share his views re the most desirable approach to teaching chemical engineering thermodynamics. This he has done. □

WHAT IS CACHE?

Continued from page 86.

WHAT LIES IN THE FUTURE?

IN THE FACE OF RAPIDLY changing technology, CACHE continually seeks to improve its ongoing activities and undertake new initiatives.

Setting up a Network. CACHE is attempting to arrange a network to serve as a reservoir for programs and data bases of benefit to educators. The network will provide billing facilities, instructions and services for programs, and local connections to gain entrance to the network.

Computer Aided Instruction. The computer-based PLATO educational system which provides interactive, self-paced instruction to large numbers of students has been widely used in physics, chemistry, and a variety of other fields with success. Professor Eckert and other faculty have been developing PLATO lessons for approximately two years starting with a series of lessons for use in the first chemical engineering course. CACHE hopes to assist in the preparation and dissemination of material of this type.

Personal Computing. The proliferation of programmable hand-held calculators and personal mini-computers is creating an environment for widespread collaboration in the preparation of programs and associated lessons. Already under way, under CACHE auspices, is a project to develop programs to allow chemical engineering students to carry out calculations for unit operations and the design of equipment.

Data Base Management Systems. The role and scope of integrated data base systems for plant design, construction and operation is being studied.

FINANCIAL SUPPORT

FINANCIAL SUPPORT FOR CACHE activities comes from donations by over 80 departments of chemical engineering in the U.S. and Canada, overhead from grants and contracts from governmental agencies such as the National Science Foundation, and industrial grants. The Monsanto Company has provided direct grants to CACHE to cover expenses in making FLOWTRAN available to educators, and has budgeted considerable internal personnel time to cover the cost of installing and maintaining FLOWTRAN. The Exxon and Shell Foundations have also provided financial support to CACHE.

SUMMARY

CACHE has succeeded in (1) stimulating interest in developing new computer based materials to be used in chemical engineering education, (2) avoiding the duplication of effort via cooperative projects and the sharing of resources, and (3) promoting new methods of distributing educational materials. It also has served as a model for similar organizations in other professions. We have found by experience that volunteer participants must be active in their own schools in developing and using computer based tools, not just sympathetic to the cause. We also have learned that projects of merit take a long time to evolve and must be vigilantly pursued if they are to reach fruition.

CACHE would be glad to hear from any faculty member who would like to participate in existing CACHE activities or initiate a new activity. Write to CACHE, Room 66-309, M.I.T., 77 Massachusetts Avenue, Cambridge, Massachusetts 02139. □

ChE news

CACHE AWARDS GIVEN

Two persons from Monsanto Company have been honored by CACHE for their contributions to chemical engineering education. CACHE president David Himmelblau awarded plaques to F. E. Reese, Senior V. Pres., Facilities and Materiel, and Dr. James R. Fair, director, engineering technology. CACHE cited the two men for their efforts in making the company's FLOWTRAN system available to the organization.

BERG RUNS ON . . . AND ON

A recent newspaper release states that although Lloyd Berg has retired from his record-breaking 33 years as chairman at Montana State, he has not retired from jogging. Both he and his wife continue their "running ways" and train for and enter marathons at the drop of a jogging shoe, often setting records in the process. Berg also stays active in the ChE arena through teaching a full load and through his research projects in solvent-refined coal.

ChE book reviews

AN INTRODUCTION TO CHEMICAL ENGINEERING KINETICS IN A REACTOR DESIGN

By Charles G. Hill, Jr.
John Wiley and Sons, 1977
Reviewed by Kenneth J. Himmelstein
University of Kansas

This text is intended to be an introductory text to Chemical Reactor Kinetics and Reactor Design. It covers in detail the thermodynamic and kinetic considerations that enter into the reactor design process.

The major subjects which need to be included in such a text are done well, including the use of concepts in reactor and chemical kinetics, basic development of reactor design, as well as covering such topics as non-ideal flow, thermodynamic considerations, and optimization techniques.

The book combines some of the best features of its most recent predecessors in reaction engineering textbooks. The development of the key concepts of the book are considered in greater detail and based on a more "first principles" approach than previous texts. Yet, it avoids the very abstract A → B approach by combining the detailed derivations and presentations with concrete examples which are based on data from real situations. This combined approach allows the author to present more deeply those concepts which the student should take from any introductory course to be applied in future years, while at the same time allowing the student to feel that he is studying real chemical engineering as opposed to some abstract classroom exercise. The attention to detail in this book is outstanding and gives the student a significant feel for problems associated with design of chemical reactors. This text is richly illustrated and documented, well referenced, and provides appropriate thermochemical data.

The major problem with the book is its organization. The first seven chapters (forty percent of the book) are devoted to chemical kinetics, while the last eight chapters are largely devoted to design of chemical reactors. Thus, there is marked division between analysis and synthesis. The student is not introduced to the concept of a reactor except very briefly until the book has used approximately 250 pages. This is undesirable in that the art of synthesis is best appreciated when the science the student learns is immediately applied practically. For instance, some of the basic concepts of heterogenous catalysis covered in the section on chemical kinetics are not used until much later. The student looses the chance to employ the details presented by the authors and must go back and review or relearn the material. There is an additional problem of organization in that the determination of reaction rate expressions is covered in the third chapter while the basic concepts of chemical kinetics (the molecular interpretations of kinetic phenomena) is not covered until the fourth. Thus, the student is left to guess at rate expression forms without any knowledge of why those forms are appropriate.

Finally, as a concluding chapter to the book, the author includes two illustrated problems of extended length and detail in reactor design. These extended problems are extremely valuable and offer significant improvement over the previous texts, in that it certainly considers the widely varying considerations that one must include in a complete reactor design.

In conclusion this book is a well detailed, somewhat deeply developed, treatment of chemical kinetics and reactor design to be used as an introductory text. It does its job well except for organizational problems. It is excellent an basis for a one or two semester course in chemical reactor engineering. □

INTRODUCTION TO OPTIMIZATION THEORY

By B. S. Gottfried and J. Weisman
Prentice-Hall, 1973
Reviewed by Thomas F. Edgar
University of Texas at Austin

This book is written as a formal exposition of optimization theory. As such, it does not appear to be suitable for the first exposure to the subject of optimization, either for an undergraduate student or a practicing engineer. Although this text probably could be used in a graduate course in optimization, the subject matter is more heavily slanted towards the operations researcher than towards the chemical engineer.

Introduction to Optimization Theory does not present a point of view which differs significantly from that available in existing tests. There are very few new insights or approaches used in the authors' development of optimization theory or algorithms. Therefore the selection of this textbook over others will rest upon how well it matches the specific topics to be covered and the depth of coverage of a given course.

The chapters cover necessary and sufficient

conditions for an optimum, one-dimensional optimization, unconstrained optimization, linear programming, nonlinear (constrained) optimization, staged system optimization, and optimization under uncertainty and risk. The last topic is the only unconventional chapter in the book. The chapter on linear programming takes a reasonably fresh, although rigorous, viewpoint. The LP presentation is not based on a cookbook manipulation but on vector-matrix manipulations. It is precisely this pedagogy, however, which makes the book non-introductory in nature.

The book will not help bridge the gap between theory and practice; very few complicated or real-world examples are worked out and presented. Another deficiency is that very few numerical details are provided, which would help the reader understand the computer "behavior" of various algorithms. Very few direct comparisons of comparable algorithms via common problems are drawn. At the end of several chapters, the authors give their recommendations on which methods to use for different types of problems, but their comments tend to be superficial and to ignore the many studies on optimization algorithms that have been undertaken. For example, the authors state that it is not possible to generalize upon the performance of existing nonlinear programming algorithms, a point with which I disagree. The authors devote only one paragraph to Powell's non-derivative method; it certainly deserves more. They also fail to point out some obvious deficiencies of some algorithms; e.g., the fact that the Davidson-Fletcher-Powell method becomes disadvantageous for large problems.

This book, like several others published recently, also includes a chapter on optimization of functionals. I have mixed feelings about including such a topic, since a single course on optimization must by necessity devote 95% or more of the lectures to static optimization. Therefore, such a topic is of dubious value in a book like this, except for limited self-study. In order to gain the proper perspective and background for optimization of functionals, the interested student or professional should take a course or read a book devoted exclusively to optimal control.

In summary, *Introduction to Optimization Theory* is a noble effort to use a rigorous, interdisciplinary approach for developing various optimization techniques. Its notation is clear, but to most chemical engineers the material and examples presented will seem a little sterile. □

RECYCLE REACTOR

Continued from page 82.

APPLICATIONS

EQUILIBRATION TIMES WERE determined by continuously monitoring the effluent composition with an infrared CO_2 analyzer. Steady state was generally realized in 30-60 minutes. Consequently, a large amount of data can be obtained in a relatively short time, making this system ideal for both undergraduate catalyst characterization experiments and graduate level research. Furthermore, catalyst beds can be easily changed, allowing the ready investigation of many different types of catalyst.

CONCLUSIONS

No laboratory reactor is truly ideal; nevertheless, the recycle reactor appears to offer a practical and educational solution to many of the problems which plague heterogeneous catalytic investigations, insofar as it offers isothermal operation at easily measured conversion levels. □

ACKNOWLEDGMENTS

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REFERENCES

1. Anderson, J. B., Chem. Eng. Edn. *5*, 78 (1971).
2. Baiker, A. and W. Richarz, Chem. Eng. Edn. *12*, 112 (1978).
3. Berty, J. M., Chem. Eng. Prog. *70* (5), 78 (1974).
4. Brown, C. E. and C. O. Bennett, AIChE Journal *16*, 817 (1970).
5. Carberry, J. J., "Chemical and Catalytic Reaction Engineering," McGraw-Hill, New York (1976).
6. Cardoso, M. A. and D. Luss, Chem. Eng. Sci. *24*, 1699 (1969).
7. Choudhary, V. R. and L. K. Doraiswamy, Ind. Eng. Chem. Proc. Des. Dev. *11*, 420 (1972).
8. Doraiswamy, L. K. and D. G. Tajbl, Cat. Rev.-Sci. & Eng. *10*, 177 (1974).
9. Gates, B. C. and J. D. Sherman, Chem. Eng. Edn. *9*, 124 (1975).
10. Makar, K. and R. P. Merrill, Jl. Catalysis *24*, 546 (1972).
11. Peiffer, C., Chem. Eng. Edn. *4*, 138 (1970).
12. Tajbl, D. G., J. B. Simons and J. J. Carberry, Ind. Eng. Chem. Fundls. *5*, 171 (1966).
13. Vejtasa, S. A. and R. A. Schmitz, AIChE Journal *16*, 410 (1970).
14. Viselov, N. G., et. al., Int. Chem. Eng. *14*, 48 (1974).
15. Weekman, V. W., AIChE Journal *20*, 833 (1974).
16. Weller, S. W., Chem. Eng. Edn. *10*, 74 (1976).
17. Williams, R.D., Chem. Eng. Edn. *7*, 148 (1973).

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