

CEE

chemical engineering education

VOLUME XIII

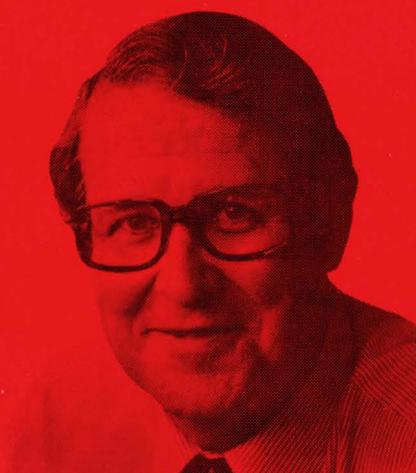
NUMBER 1

WINTER 1979

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

CHE AT N.C. STATE

ARIS OF MINNESOTA



FLUID MECHANICS CAN BE FUN

Robert F. Blanks

WHAT IS CHEMICAL STOICHIOMETRY?

William R. Smith and Ronald W. Missen

MODELS FOR TURBULENT TRANSPORT PROCESSES

James C. Hill

AN ENTRANCE REGION MASS TRANSFER EXPERIMENT

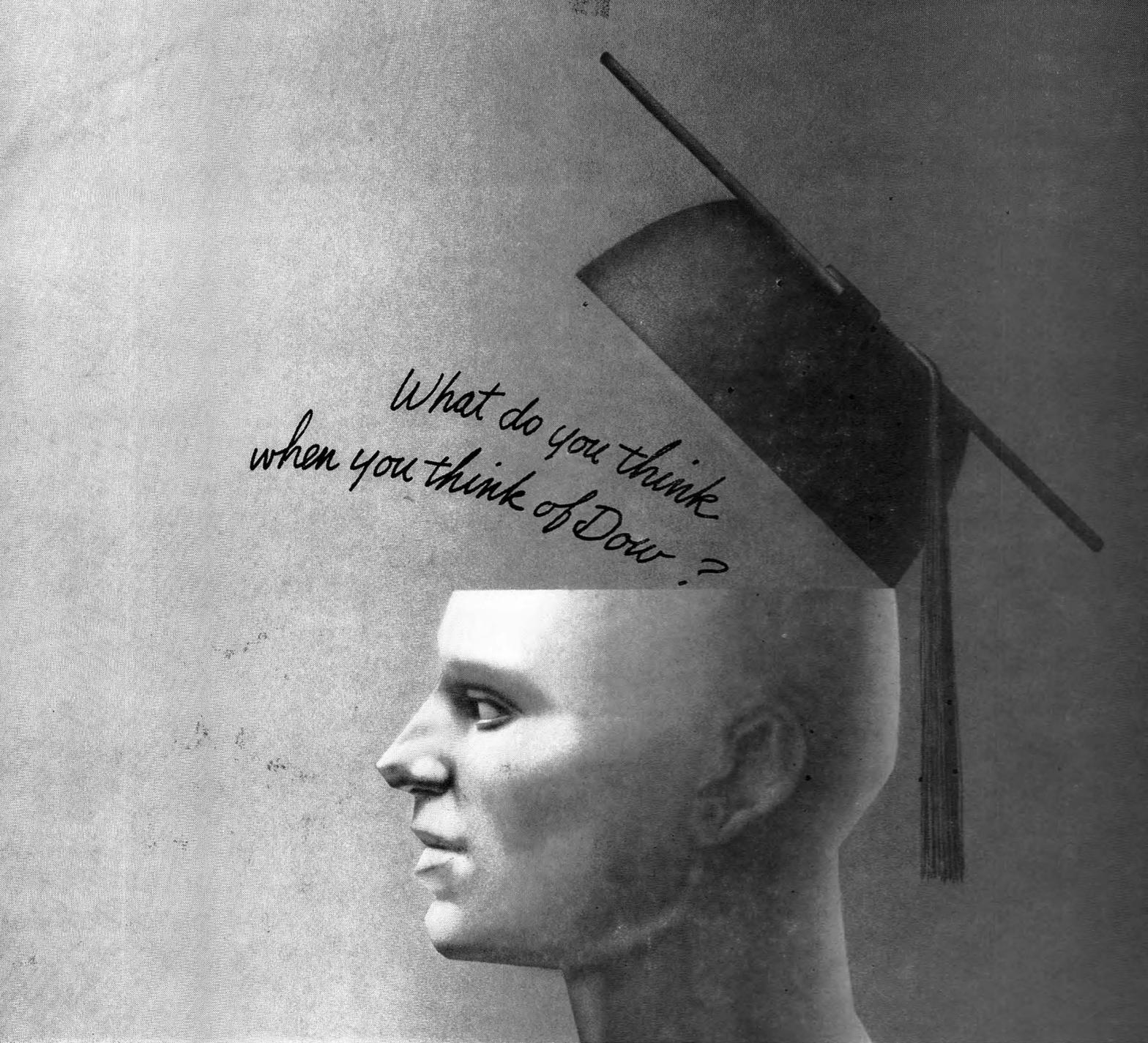
G. R. Youngquist

A 15 MONTH MS CHEMICAL ENGINEERING DEGREE FOR BS STUDENTS

Richard Hanks and John L. Oscarson

RENEWED EMPHASIS ON TECHNICAL COMMUNICATION AT TEXAS TECH

Richard Wm. Tock and Charles Brewer



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NC STATE

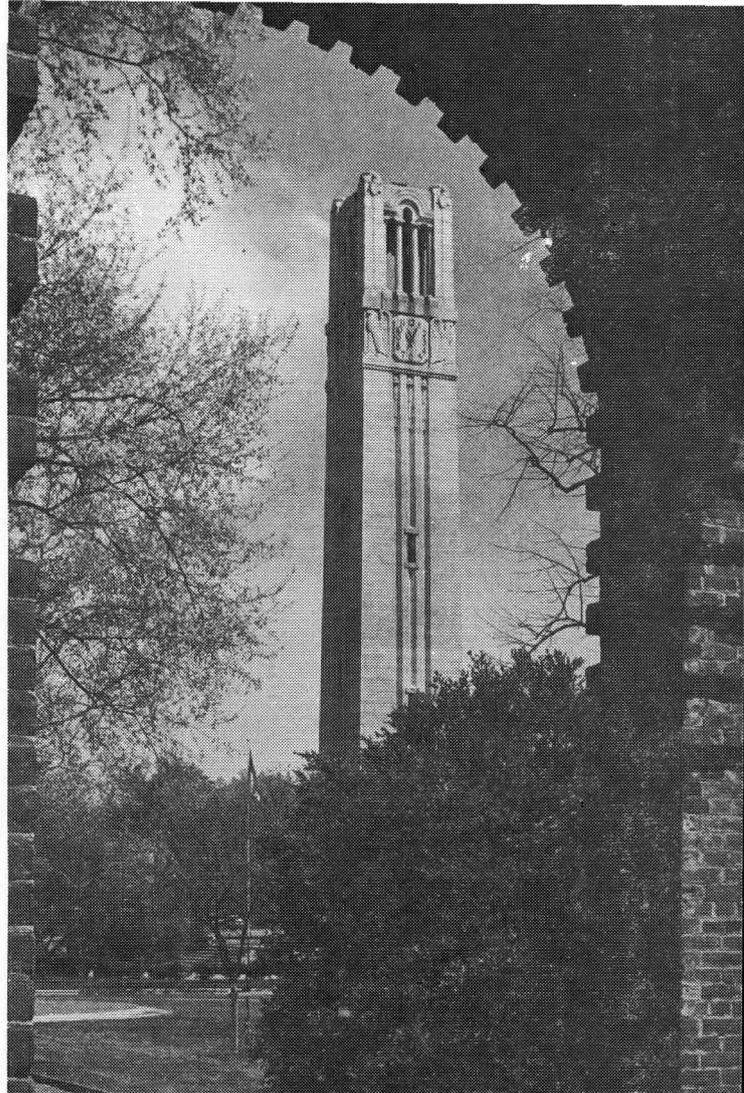
RICHARD M. FELDER
*North Carolina State University
Raleigh, North Carolina 27650*

TO SEE THE CHEMICAL Engineering Department at N. C. State in perspective, it helps to know something about the region in which we are located.

You can find grits, greens, and southern hospitality in and around Raleigh; you may also find the New York Philharmonic, Beverly Sills, the Royal Shakespeare Company, the Marx Brothers, and the Rolling Stones. Raleigh is the capital and the cultural center of North Carolina. It lies at one apex of the Research Triangle, a region bounded by lines connecting North Carolina State University at Raleigh, the University of North Carolina at Chapel Hill, and Duke University at Durham. Within the Triangle—about 12 miles from Raleigh—is the Research Triangle Park, a 5,500 acre campus for industrial and government research laboratories, including the National Environmental Research Center of the U. S. Environmental Protection Agency, and the new National Center for the Humanities. More Ph.D.'s per capita live in the Triangle area than anywhere else in the country.

While Raleigh itself is a relatively small, attractive, and uncongested city, the close proximity of the major universities and research institutions in the Triangle affords a range of activities normally found only in major population centers. The leading performers in the world regularly appear in series and individual concerts of orchestral and chamber music, dance, drama and musical comedy, jazz and rock. Classic film series and first-rate college athletics—particularly the heated rivalries of Atlantic Coast Conference football and basketball—also provide much entertainment to area residents.

Moreover, since Raleigh is situated near the geographical center of North Carolina, all of the recreational and scenic attractions of the state are within easy driving distance. The Blue Ridge and



The Bell Tower, traditionally the symbol of North Carolina State University.

Great Smoky Mountains offer some of the most spectacular scenery in the eastern United States, and North Carolina's shoreline contains many of the most unspoiled and uncrowded beaches along the Atlantic coast.

THE UNIVERSITY AND THE DEPARTMENT

NORTH CAROLINA STATE University was founded as a land-grant college in 1887, and currently has an enrollment of about 15,000 undergraduates and 2,500 graduate students. The School of Engineering is one of the ten largest in the United States. The technical resources on campus, including a million-volume library, and the ease of interaction with the other Triangle universities provide a stimulating environment for study and research.

The Department of Chemical Engineering—the only ChE department in North Carolina—occupies 40,000 square feet in Riddick Engineering Laboratories, located in the center of the main

campus. The current department enrollment is roughly 375 undergraduates and 50 graduate students, the latter working for M.S., M.Ch.E. (non-thesis), and Ph.D. degrees. The undergraduate enrollment represents a nearly three-fold increase in three years, and has imposed considerable stress on classroom and staff resources; nevertheless, all departmental courses are still routinely taught by faculty members.

The most prominent of the department's research facilities is a \$2.4 million computer-controlled fluidized-bed coal gasification and acid gas removal pilot plant—as far as we know, the only facility of its kind in the world—located in a three-story high bay area in Riddick Laboratories. The facility was constructed by Acurex Corporation under contract to the EPA, and was brought on-stream in the summer of 1978. During construction of the plant, an associated instrumental laboratory for exhaustive analysis of gas, solid, and liquid feed and effluent streams was assembled, and a dedicated microcomputer was installed for data logging and processing.

Other department facilities include well-equipped laboratories for research in polymer science and engineering, membrane transport processes, crystallization and other separation processes, phase equilibrium thermodynamics, and infrared imaging thermography. A 10-MW Pulsar nuclear reactor located in a neighboring building serves as a source of short-lived radioisotopes for tracer studies, and a Co-60 gamma source is available for studies of radiation polymerization. The Department has its own fully-staffed machine and electronics shops, and faculty members and graduate students have ready access to such specialized equipment as electron transmission and scanning microscopes maintained by the University's Engineering Research Services Division.

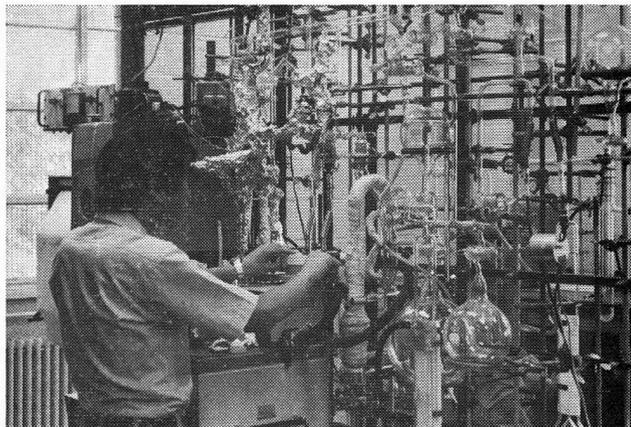
HISTORY

THE ORIGINS OF ChE at N. C. State are somewhat fuzzy. To the best of anyone's knowledge, the Department was founded sometime in the period 1923-25 by E. E. Randolph, a professor of chemistry, who served as Department Head until

The most prominent of the department's research facilities is a \$2.4 million computer-controlled fluidized-bed coal gasification and acid gas removal pilot plant—as far as we know, the only facility of its kind in the world . . .

1945. In 1935 the Consolidated University of North Carolina was formed, and all engineering degree programs in the State, including a ChE program at Chapel Hill, were moved to Raleigh.

In 1941, J. Frank Seely, an alumnus of the University, joined the faculty after a two-year internship with Texaco. Frank is still here, occupying the positions of principal undergraduate advisor and principal source of wisdom and com-



Dr. H. Kubota, a postdoctoral research associate from Gunma University, Japan, performs research on gas transport in high polymers.

mon sense to both students and faculty members. In November 1945, Edward M. Schoenborn took on the department leadership after ten years at the University of Delaware, three of them in fruitful collaboration with Allan Colburn. Kenneth O. Beatty jr. joined the faculty in the fall of 1946, after several years at Dow Chemical, four years at the University of Rhode Island, and nearly three years at the University of Michigan, where he earned his Ph.D. under Donald Katz.

At about this time, a curriculum modernization was undertaken, and emphasis shifted from courses in topics like water demineralization and gas engineering to such innovative areas as unit operations, thermodynamics, and reaction kinetics. Following an inspection by B. F. Dodge in 1948, the program was fully accredited, and authorization to award the Ph.D. was granted in 1949.

A number of faculty members no longer in the department came during the 1950's, including F. P. Pike (now retired from the University of South Carolina), Don Arnold (Kerr McGee), F. M. Richardson (N. C. State Department of Engineering Research), Bob McAllister (Dean at Lamar University), Russ Hazelton (University of Louisville), John McGee (Department Head at



The noon bridge game in the AIChE student chapter lounge is a department fixture.

Tennessee Tech), and Tom Godbold (Vanderbilt). It was also in the 1950's that James Ferrell, the current Department Head, earned the department's first Ph.D. under the direction of Professors Beatty and Richardson. Jim left the campus for a tour of duty in industry and returned in 1961, shortly before Donald Martin (from N. C. State), David Marsland (from Cornell) and Edward Stahel (from Ohio State) also joined the growing staff.

In 1965 the legendary Warren McCabe came to N. C. State after retiring as Dean of the Faculty at Brooklyn Polytechnic Institute. "Mac" remained active in research until his second retirement in 1975, and his periodic visits continue to be a source of pleasure to us.

A series of changes took place in the late 1960's, beginning in 1966, when Ed Schoenborn stepped down as Department Head and was succeeded by Jim Ferrell. In 1967 the University was awarded an NSF Science Development Grant, which served as the basis for recruiting the eminent polymer chemist Vivian Stannett, who received his doctorate at Brooklyn Polytechnic Institute. Shortly thereafter, Harold Hopfenberg came from MIT by way of Vietnam.

Later arrivals, their schools, and the years they came include Richard Felder (Princeton, 1969), Ronald Rousseau (LSU, 1969), James Helt (Iowa State, 1976), William Koros (University of Texas, Austin, 1977) and Peter Fedkiw (University of California, Berkeley, 1979). The faculty is rounded out by the presence of two joint appointees: Robin Gardner (Penn State, 1967), who spends most of his time in the Nuclear Engineering Department, and Michael Overcash (Minnesota, 1972), who resides in the Department of

Biological and Agricultural Engineering, and by Henry Smith, who graduated from this Department in 1938, received his Ph.D. from the University of Cincinnati, and came back in 1965 to assume the position of Associate Dean for Research and Graduate Programs. In 1975-76 Stannett became Dean of the Graduate School and Martin was appointed Head of the Department of Computer Science, positions they still occupy, although Stannett also actively continues his departmental research activities.

In 1976, the department inaugurated a rotating visiting professorship. We were fortunate to obtain as the initial occupant of this position, Professor Peter Danckwerts, Shell Professor of ChE and long-time Head of the ChE Department at Cambridge University, who was with us for the 1976-77 academic year. We have subsequently enjoyed visits from Dr. John Petropoulos of the Demokritos Nuclear Research Center, Athens, Greece, in the Spring of 1978, and Professor Giulio Sarti of the University of Naples, in the Fall of 1978.

DEPARTMENT RESEARCH ACTIVITIES

A UNIQUE FEATURE of the department is the frequency of intra-department collaboration, with the collaborators shifting from one project to another.

Beatty and Ferrell have long-standing interests in heat transfer and fluid dynamics. Ferrell has contributed a number of papers on the heat pipe and heat transfer in molten salts, and Ferrell and Stahel wrote the annual IEC heat transfer review for several years. Beatty's interests are currently focused on the use of infrared imaging thermography as a research tool in heat transfer, fluid flow, and biomedical engineering.

Ferrell, Felder and Rousseau are the principal and co-investigators on an EPA-sponsored study of coal gasification and acid gas cleanup, research centered on but not confined to the previously mentioned pilot plant facility. Their studies include research on the thermodynamics and kinetics of individual plant operations, evaluation of alternative acid gas removal processes, and development of methods and systems for sampling and

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Several years ago a young assistant professor searching for a way to tell freshmen what ChE is all about thought of outlining the production of alcohol from corn—a process reputedly important to the economy of certain regions of North Carolina.

analysis, monitoring and control, data acquisition, and data base management.

Ferrell and Rousseau are carrying out fundamental studies of adsorption phenomena, and have worked on the development of adsorbant materials for use in protective overgarments. Felder, Ferrell and Koros are studying the use of polymeric interfaces for *in situ* monitoring of stack emissions; Felder and Ferrell recently received a patent for the development of a probe that permits continuous unattended monitoring in dirty or corrosive stack environments for long periods of time. Felder and Rousseau have written a stoichiometry text, *Elementary Principles of Chemical Processes*, published by Wiley in 1978.

Rousseau collaborated with McCabe in research on nucleation and growth phenomena in crystallization operations, and he has continued in this field since McCabe's retirement. A recent outcome of this research is a process to use selective nucleation to separate solutes from doubly saturated solutions. Rousseau and Schoenborn studied vapor-liquid equilibria in systems containing non-volatile salts; Rousseau has extended this work to formulate predictive models, and currently is also investigating phase equilibria of acid gas absorption systems.

A monumental body of work in the field of polymers and membrane transport processes has emerged from the efforts of Stannett, Hopfenberg, Stahel, and Koros, working individually and in various combinations. Stannett is an author or coauthor of over 200 papers on most aspects of polymerization, including applications in fiber and wood and paper science. Hopfenberg and Koros conduct research on the transport of gases and liquids in polymers. Hopfenberg has investigated membrane separation processes, including ultrafiltration and reverse osmosis, and is currently working on the development of selective ion separation processes, membrane barriers for the controlled release of drugs, and liquid membrane technology. Stannett and Stahel carry out research on radiation-initiated polymerization, including pilot plant studies.

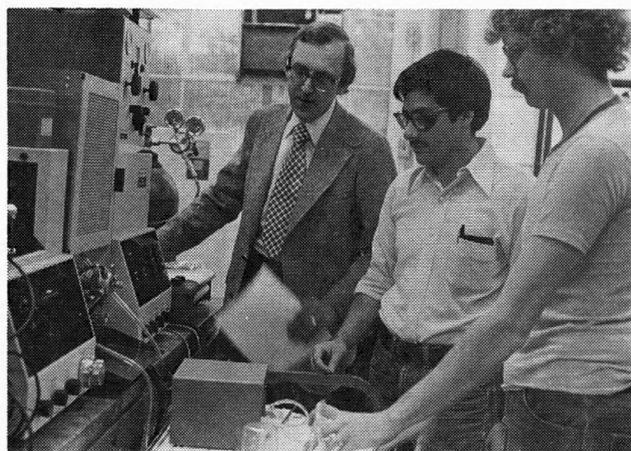
Stahel and Felder have both worked in the

field of photochemical kinetics. Stahel is currently performing research on atmospheric pollutant production, and, jointly with members of the NCSU Plant Pathology Department, on the design of chemical reactors for use in the study of pollutant uptake rates and pollution effects on plant growth.

Marsland's interests center on engineering economics, particularly as applied to pollution abatement and control, and on computer solutions of the partial differential equations of transport phenomena. Gardner studies industrial radioisotope applications, and he has used radiotracers to perform fundamental research into particulate size reduction operations.

Among the newer members of the faculty, Helt is interested in nucleation phenomena in crystallization, lubricating oil rerefining processes, and ChE applications of nuclear fuel cycles; Koros is conducting research on the sorption and transport of gases in glassy polymers, with applications to residual monomer removal and the design of gas separation processes; and Fedkiw's principal interests are in the field of electro-chemical engineering, including electrorefining and selective ion recovery.

A number of awards and honors have accrued



Professor Ferrell, graduate student Victor Agreda, and laboratory technician Larry Hamel analyze a coal sample using an atomic absorption spectrophotometer.

to the faculty. Stannett received the first Silver Medal Award of the Paper Synthetics Division of TAPPI, the Education Service Award from the Plastics Institute of America, the Gold Medal and International Award of the Society of Plastics Engineering, and from the American Chemical Society, the prestigious Borden Medal of the

Plastics and Coatings Division and the Anselm Payen Medal of the Cellulose, Wood and Fiber Division. Hopfenberg won the first Alcoa Foundation Engineering Research Achievement Award given at North Carolina State University. Hopfenberg, Felder, and Rousseau have each won the Sigma Xi Faculty Research Achievement Award, and Hopfenberg and Felder have won Outstanding Teacher Awards and have been elected to the NCSU Academy of Outstanding Teachers.

Beatty has served as chairman of the AIChE Heat Transfer and Energy Conversion Divisions and the National Heat Transfer Conference Coordinating Committee, and with E. R. G. Eckert, organized the seven nation Assembly for International Heat Transfer Conferences. Ferrell has also served as chairman of the AIChE Heat Transfer Division, and Rousseau as chairman of the AIChE Forest Products Division.

OTHER FACULTY INTERESTS

A BROAD RANGE OF interests characterizes the non-professional activities of the faculty. An unusually high proportion of guitarists can be found: Ferrell and Felder play classical guitar, Hopfenberg is an ex-rhythm guitarist in a rock combo, and Gardner plays folk guitar, specializing in off-color ballads about various marine animals. Ferrell also makes exceptionally fine guitars, not to mention a white wine that must be tasted to be believed.

Hopfenberg is a formidable gourmet chef, whose forte is quick-stir Chinese cookery but who also tosses off Northern Indian, Northern Italian, and Southern Yonkers specialties with flair and zest. Rousseau, who comes from Baton Rouge and believes he is currently living in the North, is an ex-jock who likes Cajun music, whatever sport it is that Johnny Bench plays, Thomas Wolfe novels, and a type of cooking which he swears is authentic Creole from the heart of the Bayou, but which anyone who knows anything immediately recognizes as imitation Lower East Side Delicatessen. Gardner is the other department jock—mostly tennis, with a little lunchtime basketball for variety.

Seely is one of the few native North Carolinians to be found in Riddick Labs. His principal activities include golf and wandering around the United States. Several years ago a young assistant professor searching for a way to tell freshmen what ChE is all about thought of outlining the production of alcohol from corn—a process re-

putedly important to the economy of certain regions of North Carolina. The process was not described in Shreve or any of the other standard references. The young man thought of asking Frank Seely if he knew anything about it . . . and was rewarded with a recitation of feed compositions, catalytic agents, optimal operating conditions, and residence times to four significant figures. The young professor asked Frank how he knew all that, and the subject was abruptly changed.

Stannett is a chronic globetrotter, and the leading department raconteur. Schoenborn is another habitual world traveller, and is also a classical pianist. Overcash likes politics and junkets to the Far East. Beatty has devoted much time and energy to devising aids to the blind, including devices for typing and computer transcription of Braille, and multilevel polymer maps. Stahel is an avid sailboater and antique collector; he also occasionally designs palatial manors, which he then lives in.

Marsland is one of the prime movers and shakers of barbershop quartet singing in Raleigh and environs. Martin is active in local community affairs, and is also a Commander in the Navy Reserve; he looks magnificent when he wears his dress whites to class, and his happiness would be complete if only people would stop asking him to hail them a taxi when he stands in front of a hotel.

Helt and Fedkiw are hikers and campers. Koros is also a hiker, and an enthusiastic paddleboater. He makes superb coffee but he has the strangest ideas of what barbecue is supposed to taste like, and in other ways tries to project a Texas macho image; if he ever succeeds in intimidating his small dog into staying out of the living room he may convince the rest of us that it's legitimate. Felder is a devotee of Gilbert and Sullivan and Ursula LeGuin, and is a card-carrying hedonist. He has no known faults or eccentricities.

Most of the faculty consider themselves outstanding pool and poker players. They prove themselves wrong every year at the annual Christmas party in Frank Seely's basement. Marsland, Ferrell, Felder, Gardner, Hopfenberg, Beatty, and Stahel are passable bridge players, who have on occasion dropped by the department lounge to give the graduate student regulars a lesson or two. The uniqueness and individuality of the faculty is attested to by the fact that as of this writing, to the author's best knowledge, not one of them jogs! □

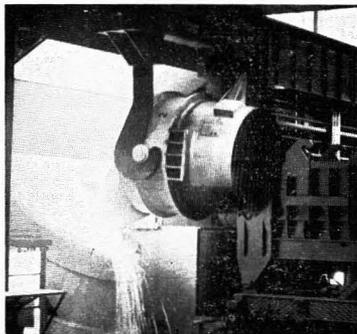
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JUST ABOUT EVERYONE with an interest in the subject, both in and out of Who's Who, knows that Aris Rutherford is a mythical character; created as a well-deserved admonishment to a pompous bureaucracy by a gentleman and scholar named Rutherford Aris. The more serious matter to anyone who takes on the task of describing him is to recite the facts and still convince the reader that Rutherford Aris is not himself mythical.

In the 23 years since he first came to Minnesota, Aris has compiled a record of scholarship which has few equals in chemical engineering. Nine texts and monographs, several book chapters, and over 150 journal articles attest to the quantity of the record; the spate of awards he has received, the special lectureships to which he has been appointed, and his membership in the National Academy of Engineering attest to its quality. But impressive as this record is, it tells only a small part of the story of a man who has been variously described by his colleagues in and out of ChE as ". . . a saintly genius in the secular domain of scholarship and seminal research . . .," ". . . the most scholarly chemical engineer I know . . .," ". . . one of the last remaining polyhistor . . .," ". . . one of the few university professors today who master the nearly lost art of speaking correct English. . ." and ". . . my one colleague in chemical engineering who shares an interest in Real Tennis. . ."*

Fulsome praise? His colleagues at Minnesota, where he has recently been made a Regents' Pro-

*The authors of each of these documented quotes will remain anonymous, but several can be guessed. It is a game Gus Aris would enjoy. Four out of five correct answers rates an A and the Exxon Suite Award.

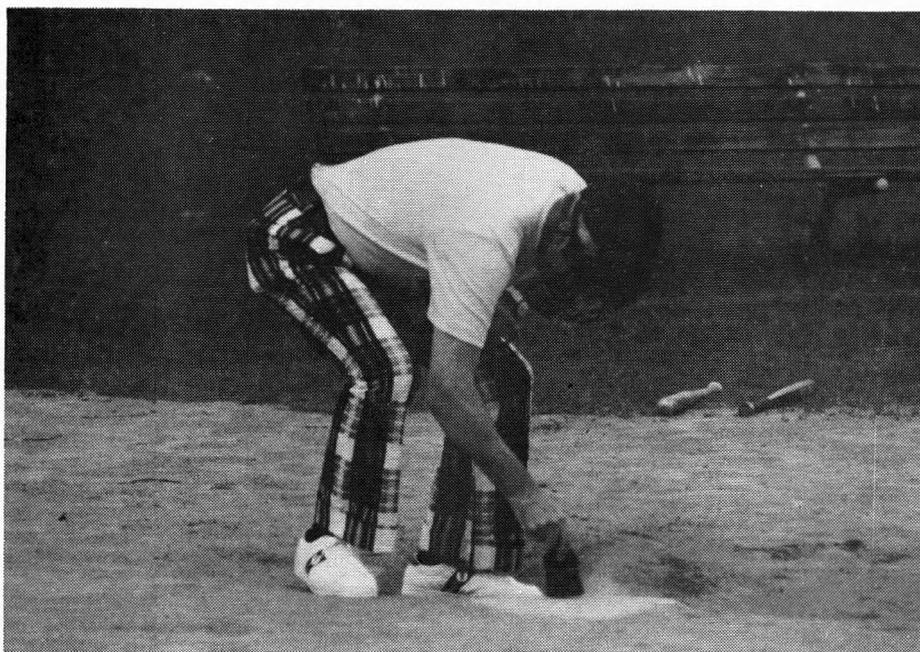
fessor—one of 15 among the faculty of some 3000—would not think so. For in the institution at which he has spent his entire teaching career, Gus Aris is something of a Renaissance man. It will undoubtedly come as no surprise that he offers courses in Chemical Reactor Analysis and in Mathematical Methods; elegant, axiomatic renditions of the principles which have attained a central role in ChE today. But he has also frequently offered courses and lectures on Medieval Manuscripts and The History of Latin Handwriting and is working on a monograph on medieval paleography. He is involved in collaborative re-

. . . he . . . earned an external degree
(B.Sc. in mathematics) from London after two
years of spare-time study at the ripe old age of 19.

search with a colleague in History on developing mathematical techniques for dating documents of the period from 900-1150 A.D. and he has played a role in the evolution of courses in Science and the Humanities. In fact, these kinds of contributions have become so regular that this fall the University formalized the arrangement by making him a *de facto* University Professor, freed half-time from his ChE responsibilities to follow his inclinations in these other fields. Thus, for the very mythical Aris, there is now a new beginning—which, naturally, stimulates recollections of his first beginning.

ENGLISH BEGINNING

RUTHERFORD ARIS WAS BORN in Bourne-mouth, on the south coast of England, in September of 1929, a fact that 20 some odd years in the upper midwest, marriage, baseball, basketball, and football have absolutely failed to overcome in any way.



**As an Englishman,
Aris does not claim a
deep knowledge of baseball,
but he knows where to begin.**

According to authoritative family sources, young Rutherford, the second of four children, first exhibited his interest in abstract quantitation by taking charge of the family shopping list. With that to build on, he went on to Canford, an English public school, and earned an external degree (B.Sc. in Mathematics) from London after two years of spare-time study at the ripe old age of 19. He had already joined Imperial Chemical Industries as a "technical officer" and was working in Edinburgh with C. H. Bosanquet, one of Britain's early engineering scientists, when Neal Amundson, on sabbatical, arrived on the scene in 1955. In the classic paradigm of the graduate student recruiting we all know so well today, he convinced Rutherford to come back with him to Minnesota, where Amundson was then beginning a building program.

Rutherford accepted, came to the United States, became "Gus" Aris and spent a year. Not a bad one, at that. He wrote what has become a classic paper on Taylor dispersion, which was published in the Proceedings of the Royal Society. He also published the first of what would be many collaborative efforts with Amundson on reactor stability. Most importantly, he met and subsequently married Claire Holman, a Minneapolis native, with whom he has shared his life since. With those ties established, he returned to Britain for a year, earned another external degree from London—this time a Ph.D. in Mathematics and Chemical Engineering—and crossed the Atlantic once again in 1958 to accept an Assistant Profes-

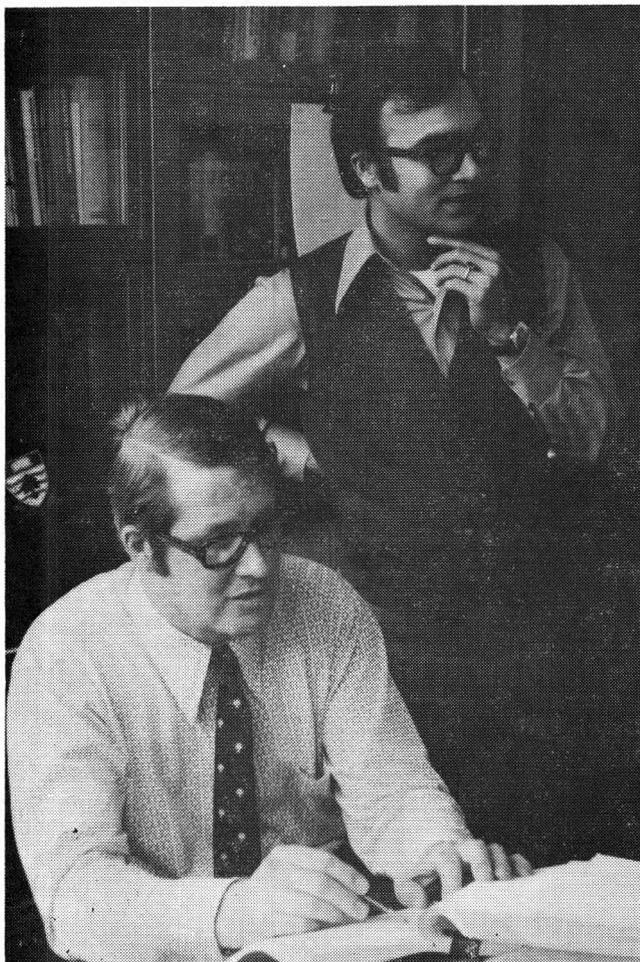
sorship at Minnesota. Since 1963, the title has been Professor and, from the Fall of 1978 onward, Regents' Professor.

AND MINNESOTA DIVERSITY

GUS' CHEMICAL ENGINEERING scholarship has, of course, focused on the effective application of mathematics to the description, understanding, and control of reacting systems. In the early years the applications were primarily in reaction engineering—control, stability, optimization. But that changed as he and his collaborators began to look at a number of other areas. They laid a strong, analytical foundation for multicomponent chromatography, and Gus began to work on biological problems of several kinds: microbial population dynamics; enzyme kinetics; membrane transport; chemotaxis. Today, he is as active in biological applications as in any other single area.

One of the reasons that Aris has been able to work effectively in a number of fields is the ease with which he is able to enter into collaborations with colleagues. No doubt the longest and closest collaboration was with "The Chief," Neal Amund-

Aris' ability to write is remarkable. Many of us have watched him sit at lunch and, in the calligraphic hand which is something of his trademark, pen the draft of a paper which, with few changes, will be sent off as a finished work.



Aris with Arvind Varma, one of his many Ph.D. students who have gone on to productive academic careers.

son, with whom Gus has coauthored almost two dozen articles and a monograph. But he has also worked at one time or another with four or five other colleagues at Minnesota and as many or more elsewhere.

Aris' ability to write is remarkable. Many of us have watched him sit at lunch and, in the calligraphic hand which is something of his trademark, pen the draft of a paper which, with few changes, will be sent off as a finished work. It is tempting to explain this ability as arising from the capacity of a mathematician for ordered thinking, but those who know him are more likely to agree that it is his love of and constant immersion in words and language that accounts for it.

This facility with words not only produces papers; it produces an array of rhymes and limericks, aphorisms and patter songs for every occasion. His specialty is the reworking of well

known (or not so well-known) poems and arias to fit more appropriately the topic or occasion at hand. When Skip Scriven was feted as Lacey Lecturer at Cal Tech last year, the Cal Tech men's chorus treated him to a rendition of "Now I am the lecturer of Cal's Lacey . . ." with suitable apologies to W. S. Gilbert and credit to R. Aris. When a lunchtime conversation on coal liquefaction turned to the use of the word liquefaction in a 17th century poem by Robert Herrick, the poem was updated by Gus. . . .

**Whenas in silks my Julia goes,
Then, then methinks how sweetly flows
That liquefaction of her clothes.**

**Next, when I cast mine eyes and see
That brave vibration each way free,
Oh how that glittering taketh me!**

Robert Herrick

**Whereas in gases fled its moles,
Now, now methinks research controls
The liquefaction of my coals.**

**I'll do it first by Fischer-T,
Take lots of points, then wait and see
Oh how that sells with D. O. E.!**

Rutherford Aris

And recently, when he was asked to attend a quasi-social meeting with some state legislators, quite aside from what the meeting may have produced for the University, the following plaint was found afterwards:

**It was just as I feared it w'd be
When I went to the lawmakers' tea,
Their rumblings abdominal
Were simply phenomenal
And they slashed both the budget and me.**

WIDE RANGING INFLUENCE

ARIS' INFLUENCE AT and on Minnesota has been broad and deep. Some elements of that influence are in the areas in which one would expect them: new course development, graduate student thesis advising (indeed, he has directed

He played a significant role in the development of programs in Religious Studies and in the History of Science at Minnesota, both large issues to him, and well worth the price of the many hours spent on small ones whose greatest value is as subject matter for quatrains and limericks.

He is as comfortable with English literature and poetry as he is with reactor analysis. . . . He is a religious man, deeply so and privately. But even that he finds a way to share with his friends at many levels—historical, philosophical, moral.

RUTHERFORD, ARIS MACPHERSON, educator; b. Strath Spey, Scotland, Apr. 10, 1930; s. Archibald MacPherson and Ephygeneia (Aristeides) R.; diploma Strath Spey and Glenlivet Inst. Distillation Engring., 1948; B.Tech., Billingham Coll. Engring. and Tech., 1952, D.Eng., 1955. Came to U.S., 1956, naturalized, 1961. Chief design engr., tester Strath Spey Distillation Co., Ltd., 1955-56; chem. engrin. cons., Chgo., 1956-60; vis. prof. distillation practice Tech. Inst. of the Aegean, Corinth, 1960-64; prof. chem. engring. U. Minn., Mpls., 1964—. Mem. County Commn. for Local Industry, Speyside Area, 1955-56. Trustee, Scottish-Greek Friendship Found., Edinburgh, 1960-64. Served with Argyll and Sutherland Regt., 1948-50. Mem. Burns Soc. Mpls., Distillation Club Edinburgh. Presbyn. Clubs: Hellenophilic (Mpls.); Woods (Gleneagles, Scotland). Author: Sampling Techniques, 1957; American Football-A Guide for Interested Scots, 1960; Distillation Procedures, 1963. Office: U Minn Sch Chemistry Minneapolis MN 55455

The infamous Aris Rutherford as advertised in *Who's Who*, 38th Edition, 1974-5.

the Ph.D. theses of 25 students thus far, several of whom, like Mort Denn of Delaware, George Gavalas of Cal Tech, and Harmon Ray of Wisconsin have already become influential in their own right). But, beyond that, Aris has interwoven his own sense of eclecticism into the fabric of the department. For example, in the early 50's he initiated a tradition in which, once every three years, the graduate seminar program for an entire quarter is devoted to topics outside of the normal purview of ChE. Lecture topics have ranged from Scandanavian literature to Brazilian folk culture; from anthropology to stage movements with many stops between. Every Ph.D. student has the opportunity to be involved with at least one such series. While several people have helped in these, it is primarily Aris who organizes them, introduces them, and ultimately oversees their publication in volumes with such titles as: *The Scope of Scholarship*; *Varieties of Academic Experience*; and *Catastrophes and Other Important Matters*.

When Amundson decided to step aside from the headship in 1974 after 25 years, Aris was the unanimous choice of the departmental faculty to take over. It was not the kind of a position that a man like Aris would relish, but it was clear that

he was the right person to lead the department through a difficult transition in a time of economic contraction. He did just that for four years, with his good sense and his scholarly sense, his patience and his wit. The evidence is, that upon stepping aside from the post in 1978, all four remained intact.

Gus has also been one of the most active faculty members in the University in faculty governance, a tribute to his sense of charity (*agape*, he would explain). Foraying into the Byzantine intricacies of University committees, using a cultivated innocence as shield and weapon ("... But, Mr. President, since the NCAA is such a problem, is this not a splendid opportunity simply to leave it, to abandon intercollegiate football and basketball. Surely we'd be better off for it and could concentrate on more important things . . ."), he has consulted, advised, adjudicated, and resolved his way through untold issues, large and small. He played a significant role in the development of programs in Religious Studies and in the History of Science at Minnesota, both large issues to him, and well worth the price of the many hours spent on small ones whose greatest value is as subject matter for quatrains and limericks.

THE RENAISSANCE MAN

AND WHAT IS ARIS LIKE outside of the context of the University? Very much the same. A man of books—books of every sort. He is as comfortable with English literature and poetry as he is with reactor analysis. He will show you his volumes of etchings and line drawings of European birds. He will leaf through a fine edition of T. S. Eliot with you. He is a man of languages—classical ones, particularly Greek and Latin, but with more than a passing interest in Norwegian and Danish. He is a religious man, deeply so and privately. But even that he finds a way to share with his friends at many levels—historical, philosophical, moral.

Then there is the Aris wit. Dry, you might say, and perfectly suited to the art of dealing with dehumanizing bureaucracies, overinflated egos, and the other social ills to which we are too often ex-

posed. Aris' particular English background recognizes class, but does not confuse it with worth nor stand in awe of it. Perhaps that explains some elements of the Who's Who story*, which, for those who don't know it, began with a letter from those good people to one Aris Rutherford inviting him to submit a biography. As one used to such errors, he wrote back kindly, explaining that he was not Aris Rutherford, but Aris (comma) Rutherford, and under that latter name, he was already a biographee in their prestigious publication. In response, he was informed by some automatic typewriter that individuals could not buy their way into Who's Who. Thus challenged, Aris Rutherford, the Scottish inversion of our English colleague, was born and given a history.

And is Aris still an Englishman? Well, there is this trouble he has understanding American football—(time outs? cheerleaders? platoons?—Whatever for?)—and these peculiar misspellings (behaviour, colour).

Finally, how, you ask, did he come to be called Gus? That has to do with India and bath water—well, not exactly bath water . . . Really, it's a long story. You'd better ask him when you next see him. □

*Editors note: See CEE, Vol. IX, No. 3, page 119, for feature article pertaining to this.

ChE stirred pots

THE REYNOLDS' NUMBER SONG

(Contributed by Peter Harriott, Cornell University)

Sir Osbourne Reynolds was a man of yore
Who liked to play with symbols that you might think a bore
But he figured out a problem and aquired some fame
And now the Reynolds number bears his name

Chorus

Take a d times a v and a rho by mu
Put them all together with a little bit of glue
Then you've got a number that will see you through
And tell you what the fluid's going to do

Does the syrup in the pipe flow as smooth as can be
Or is it all mixed up like in a cup of tea
Enter all the numbers and press the little key
Laminar or turbulent, the answer will be

Now lots of other numbers may come to mind
Prandtl, Schmidt, and Grashof, and more of that kind
But when you've got a sticky problem and are getting in a bind

The old Reynolds' number is the first one to find

It's really very simple, so the profs all say
But the gol-darn dimensions keep getting in the way
The old English system has had its day
So better switch over to SI today

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FLUID MECHANICS CAN BE FUN*

ROBERT F. BLANKS**

Michigan State University
East Lansing, Michigan 48824

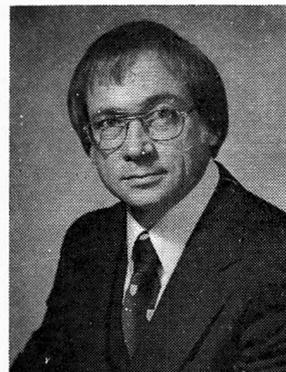
IN MY FIRST FEW YEARS of teaching engineering at the university level, I used the traditional lecture method. Homework assignments were collected and routinely graded. Course grades were assigned based upon a composite score of homework grades, grades on hour examinations, and a final examination grade. A class grade distribution was obtained from a statistical t-score analysis. Student response to this approach was generally favorable but not exciting. Several events combined to motivate me to examine alternative teaching methods.

An article in the student newspaper caught my attention and plagued my conscious thoughts. In effect, the article showed photographs of sleeping or bored students in several classrooms and posed the question, "Are these people enjoying this educational experience?". I began looking in classrooms and at my own classes with this question in my mind. For the most part, I concluded that the answer was "probably not."

At this point, I engaged in a continuing series of lengthy discussions with a woman, who is now my wife, Judy, about alternatives offered by the field of humanistic education. Judy and I attended several personal growth workshops led by Dr. Sid Simon and a values clarification workshop led by Dr. Howard Glasser-Kirschenbaum. I began reading a great deal in this area, including a book by Robert C. Hawley and Isabel L. Hawley [1]. The title of the Hawleys' book is *Human Values in the Classroom*. I began to try some of the strategies and methods I was learning in my classroom. In the fall of 1976, the experience and response in my junior class of fluid mechanics was so rewarding that I decided to share it with others by writ-

*Presented at the November, 1977 AIChE Meeting, New York Session, "Caring in the Classroom".

**Present address: Amoco Chemicals Corp., Naperville, Ill. 60540.



Robert F. Blanks: I have had approximately equal periods of experience in chemical engineering education and in industry. After obtaining my PhD in ChE at the University of California, Berkeley, I joined Union Carbide's Plastics Process R&D section in Bound Brook, New Jersey. After seven years there, having moved up the ranks with one foot on each side of the dual technical-administrative ladder, and on the verge of moving into the administrative line, an old latent urge motivated me to leave Union Carbide and join the ChE Department at Michigan State University. I taught there for nine years and was promoted to the position of Professor in 1978. During my academic tenure, I consulted with Dow, Corning Glass, and Amoco Chemicals. Although I enjoyed my classroom teaching experience, my consulting work was more rewarding. Driven by salary differential, large classes, and turned off by the grantsmanship game, I returned to industry where I am now employed as a Senior Research Engineer by Amoco Chemicals R&D in Naperville, Illinois.

ing this paper for a session at the fall, 1977, AIChE meeting. The session title is "Caring in the Classroom."

HYPOTHESES

BASED UPON THE experiences motivating me to consider alternatives to the lecture method, I offer the following hypotheses or rationale for the methodology used in the course about to be discussed. Much of this thinking comes from the Hawleys' book [1], for which I am gratefully indebted.

It is difficult for a teacher to educate students by talking *at* them, or by lecturing, in the manner of a preacher or a wise parent. Students often learn most by experiencing, by problem solving, by creating and observing the need for knowledge

and then by seeking out the knowledge from several available sources, e.g., peers, teaching assistants, books, the professor. Role playing the part of an industrial engineer on an assignment, laboratory demonstrations, intriguing problems, and analogies can combine to make the process of learning effective and enjoyable to the student.

An authoritarian, judgemental attitude on the part of the teacher can stifle creative thinking by the students. Empathetic listening by the teacher, in the classroom or on a one-to-one basis in recitations and during office hours, may create a rapport between teacher and students and among students, which often increases academic achievement. This community building can become an important aspect of planning a class. Positive reinforcement and positive feedback—from students to teacher, from teacher to students, and among students—tends to check boredom, to provide self-confidence, and to generate enthusiasm on all sides.

In planning for the teaching of any given course, it would be well for the instructor to consider elements related to the process of learning as well as those concerned with the chronological sequence of content. Areas such as community building, achievement motivation, providing for student-teacher and student-student communication, and the physical set-up of the classroom may be important concerns. Often the rigid physical arrangement of rows of desks facing a lecture stand is a limitation to open student-teacher interaction in a sharing sense. One of the teacher's first tasks is to communicate to the students the goals of the class as the teacher sees them. It is often helpful at this point to attempt to involve the students in setting goals for the class.

One concept which is often difficult for me to remember is that a group of students in a class do not function collectively in the sense of their grasp of material or response to particular teaching methods. On the contrary, a class is composed of a number of individuals with varying abilities, with unique sets of external demands upon them, who respond separately to different methods of teaching such as the lecture, group work, independent study, problem solving situations, etc. Therefore, if a variety of learning situations can be created in a classroom, or outside of the classroom, each student may seek the method in which he or she is most comfortable and most likely to learn.

A teacher may possess a great deal of knowledge in a field and it is often most efficient to pass this knowledge on to a class by means of lecturing.

However, in addition, it is important for the teacher to help the student learn how to approach problems, to develop solutions and assess the accuracy of results, to become creative thinkers, and to seek alternate sources of information. A teacher might better view himself or herself as a facilitator of learning rather than as a dispenser of information.

In the traditional lecture system, many students attempt to place the responsibility for their learning on the teacher. This responsibility belongs to the student. Self-motivation is one key to high achievement. This is a more obtainable goal when the students have played a role in establishing course objectives, have a variety of alternative learning processes available, have a good rapport with the teacher and with each other, and have even helped to establish criteria for measuring achievement. It seems very desirable to attempt to create a situation where students and teachers alike work together to help everyone achieve to the maximum of their abilities rather than an adversary situation where students attempt to outwit the teacher, or to beat each other at the grading game. The negative aspects of grading are discussed in the Hawleys' book [1] and elsewhere [2, 3]. I will not attempt to thoroughly discuss this controversial subject here. It appears to me that there is a real conflict between the negative aspects of grading, the need for honest evaluation of achievement, and the desire for company recruiters to have the students of engineering rank ordered.

METHODOLOGY

IN THE FALL OF 1976, I attempted to incorporate some features of the humanistic education approach into teaching fluid mechanics and

**Role playing the part of
an . . . engineer on an assignment,
laboratory demonstrations, intriguing problems,
and analogies can combine to make the process
of learning effective and enjoyable . . .**

heat transfer to a group of 87 junior ChE students at Michigan State University. The course was divided into two sections of 48 and 39 students, respectively. Each section met for five hours per week, 3 one-hour periods and 1 two-hour period. Two senior ChE students and one graduate student met with me and the class in the classroom.

TABLE 1
Class Outline

Text: Bennett and Myers, "Momentum, Heat, and Mass Transfer," 2nd edition, McGraw-Hill Book Co. (1974).

TOPICS

Introduction
Fluid Behavior
Overall Mass and Energy Balances
Overall Momentum Balance
Flow Measurement
Boundary Layer and Turbulent Flow
Dimensional Analysis and
 Design Equations for Fluid Flow
Heat Transfer by Conduction
Convective Heat Transfer Coefficients
Heat Transfer with Laminar Flow
Heat Transfer with Turbulent Flow
Design Eq. for Convective Heat Transfer

The course was divided into 9 topic areas with assigned problems and a one-hour examination for each area. There was a two-hour final examination at the end of the term.

The course outline is shown in Table 1. Each week began with a one-hour lecture introducing the important concepts for the week. The following three class hours for the week were devoted to problem solving sessions. Students worked together on the assigned problems in groups of two or three, or some students chose to work individually. As the Hawleys pointed out, practice in collaborative information processing can be a valuable part of the learning experience. In industrial and governmental research and engineering, teams of people develop information for use by management in decision making. Problems which sometimes seem overwhelming to an individual may be comprehensible to a group. Students working in group problem solving sessions obtain training in shared information processing and can become aware of a need for interdependence in achieving their own goals. They may develop a sense of what to expect from different types of people and learn something about the difference between unwisely trusting incompetent sources and being unwisely suspicious of helpful, competent sources [4]. They also spent some time at home with the assignment.

The student assistants and I circulated throughout the classroom during the problem solving sessions and talked to the individual student groups as the need arose. Occasionally, I

would give a short "mini-lecture" on common problem areas. The hour examination at the end of the week was structured in such a way that mastery of the concepts required to solve the assigned problems usually meant that a student could do quite well on the examination. The student's solutions to the assigned problems were not picked-up or graded, yet almost all of the students attended the problem solving sessions and attempted to work the problems. Some students attended the sessions in both sections. Some students asked for, and were given, additional problems for exercise. For two of the nine weeks, the student's problem solutions were accepted in lieu of the hour exam although an examination was also available for those that chose that alternative.

A movie on turbulence and several demonstrations in the fluid mechanics laboratory helped the students visualize the application of theory. The orientation of the course was problem solving and students were helped to role-play engineering assignments. For example, copies of the final examination questions, some from the Bennett and Myers textbook [5] are shown in the Appendix.

TABLE 2
Feedforward Form

1. How would you like to see this class run and what would you like your part to be in helping it to function in this manner?
2. What do you expect from the class leader?
3. What do you expect from yourself?
4. What special concerns, issues, or questions would you like to have considered as part of an input to this course?
5. Open comment:

EXPERIENCES AND RESPONSES

By the end of the term, I had become acquainted with all of the students on a first-name basis. This was facilitated by holding a large number of office hours and on some weeks specifically requesting that the students stop in during some portion of the office hours. I feel that an open and caring atmosphere developed within the class. On the first day of the class, the students completed a feedforward form telling about their expectations for the course, the professor, and themselves in the course. The form is shown in Table 2. Frequent feedback forms were used as the course progressed and helped to promote the openness. Complete responses to the feedback forms were

It is difficult . . . to educate students by talking at them, or by lecturing, in the manner of a preacher or a wise parent. Students often learn most by experiencing, by problem solving, by creating and observing the need for knowledge.

distributed to the students the period after they were handed in. Examples of two feedback forms are shown in Table 3 with student responses included.

The use of feedforward forms helps the students to feel that they have a role to play in setting the goals for the course. Students pause to think seriously about their expectations and goals for themselves. The feedback form helps to show a willingness to change direction and that the teacher is concerned with students feelings. Students also communicate their feelings to each other. The usefulness of feedback is discussed by the Hawleys [6]. Students may feel rather powerless over their lack of opportunity to influence the course of their educational experience. Feedback forms provide a way for the teacher to address this need. Positive feedback from the class may motivate the teacher to try even harder to give the students a valuable and meaningful experience in the classroom. Problem areas may be uncovered which can be corrected before they become serious.

Responses by the students regarding the class were overwhelmingly positive. Performance by the students on examinations was better than any previous time when I taught this subject. Most of the students commented that they felt they had really learned something in this course and a few of their comments are listed in Table 3. I felt that this was the best and most enjoyable course that I have ever taught.

CONCLUSIONS

LARGE CLASSES MAY BE taught sensitively with a significant amount of professor-student interpersonal relationship developing. The lecture mode of teaching may be successfully minimized in a difficult and demanding technical course. Group and individual problem solving sessions, with professor and teaching assistant involvement, are effective methods for learning. Frequent examinations are an effective motivation to learning and tend to ease the pressure of exam taking.

Student feedforward and feedback forms give the students a good feeling of being involved in a course and give the professor a good feeling about his/her teaching experience. An open, caring at-

TABLE 3
Feedback Forms and Responses

Responses in *italics*

On a scale of 1 to 7 with 7 being high

	7	6	5	4	3	2
The class rated	— 19	41	20	6	1	0
The lecture rated	— 19	35	27	7	3	1
The recitation rated	— 27	28	21	9	0	2
Teaching assistants rated	— 15	25	24	7	2	0
The professor rated	— 33	42	9	1	1	1

On a continuum scale from strongly disagree to strongly agree please respond to the following:

	Majority Opinions
CHE 305 requires too much time outside of class hours	<i>neutral</i>
Having 9 tests per term is better than having 4 tests per term	<i>strongly agree</i>
I feel like I'm learning some fluid mechanics	<i>strongly agree</i>

And I'd also like to say:

- *I like the approach—noncompetitiveness.*
- *I think the way the class is being conducted is great.*
- *I enjoy the course and understand the material much more than I would under standard classroom procedure.*
- *I like it when the professor remains flexible throughout the term.*
- *Best class I have ever had.*

titude on the part of the professor promotes a like response from students and a significant amount of 1:1 professor-student contact outside of the classroom. Students may be effectively motivated to learn subject material without collecting and grading homework. An open, humanistic approach to teaching engineering can result in improved student learning, self-confidence, and self-appreciation. □

ACKNOWLEDGMENTS

I would like to validate all of the people who have helped me through some significant personal growth stages in my life and who have helped me to become aware of the concept of caring in the classroom. In particular, I want to validate my wife, Judy, Sid Simon, Carrie Owens, and Carol Weiskopf. I thank the Hawleys for such a lucid presentation of valuable ideas in their book. I also appreciate the work of the teaching assistants in the class; Mike Goodnight, Barb Dittmann, and Terry Haske. Our department secretary, Ann Brown, typed all of the feedback responses

weekly without complaining and that was a significant task. Last, but not least, I appreciate the great class of students enrolled in CHE 305 last fall.

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APPENDIX Final Examination Questions

SECTION 1

1. Water is retained in a mountain lake whose surface is 280 ft above the inlet to the turbines in a powerhouse. Surveyors have laid out the best line location for the piping system to bring water from the lake down to the power house. The route is 3100 feet long. You are the engineer working for the community's power generating company. What is the minimum standard diameter of pipe which may be used in the line so that the natural flow will be 1000 gallons per minute and the pressure at the turbine inlet will be 100 psig? Assume turbulent flow. After obtaining a solution, justify the neglect of any terms in the equation required to obtain the solution and justify any assumptions made about the type of flow.
2. You are an engineer in the process development section of a polymer manufacturing company. Specify the horsepower required and the pressure which a pump must develop for the following application. Pump 5000 lb/hr of a high viscosity, Newtonian, fluid 75 feet through a 2-inch diameter transfer line. The material is being transferred from one chemical reactor at 900 mm Hg absolute pressure to another reactor at 450 mm Hg absolute pressure. The material has a viscosity of 50,000 cps and a specific gravity of 0.95. Place the pump at the exit of the first reactor. Assume that the efficiency of the pump is 75%.
3. You are the design engineer in a petroleum refinery. Oil is being cooled in the inner pipe of a double-pipe heat exchanger. The oil flows at a rate of 27,500 lbs/hr and is cooled from 100°F to 89°F. The inside tube is a 3/4" 16BWG steel tube. The oil is cooled by water flowing counter-currently at a flow rate of 8000 lbs/hr. The water enters the exchanger at 68°F. The outer tube is 3" sch 40 iron pipe. Calculate the required heat exchanger length. Oil properties are:

T°F	75	80	85	90	95	100
μ (cps)	3.9	3.7	3.5	3.3	3.1	2.9

$$C_p = 0.474 \text{ Btu/lb}^\circ\text{F}$$

$$\kappa = .0789 \text{ Btu/ft}^2\text{hr } ^\circ\text{F/ft}$$

$$\rho = 51.5 \text{ lb/ft}^3$$

4. You are a production supervisor in a food processing plant. Orange juice is being concentrated by evaporation of moisture from a film of juice flowing down the inside wall of a large pyrex tube. The tube is heated on the outside by steam at 220°F. The orange juice flavor is easily affected by overheating; therefore, no portion of the juice can have a temperature exceeding 160°F for even a short period of time. Find the limiting bulk velocity for the case where the bulk mixing-cup, temperature of the orange juice is 140°F, and the maximum O. J. temperature is 160°F.

DATA: Convective coefficient for steam: $h = 1000 \text{ Btu/hr ft}^2\text{ } ^\circ\text{F}$

Convective coefficient for the orange juice: $h = 150 u_b^{1/2}$ where u_b is bulk velocity of the film in ft/sec and h is units of $\text{Btu/hr ft}^2\text{ } ^\circ\text{F}$ (i.e., conversion factors are built into the 150)

Thermal conductivity of pyrex = $0.5 \text{ Btu/hr ft}^2\text{ } ^\circ\text{F}$

Pyrex wall thickness 1/4 inch

SECTION 2

1. You are a design engineer in a petrochemical plant. Calculate the horsepower required and the pressure which a pump must develop for the following application. It is necessary to pump benzene at 70°F from a storage tank at atmospheric pressure to a pressure vessel at 50 psig through the piping arrangement described below. The flow rate is to be 320 gallons per minute. Assume the pump to be used has an efficiency of 80 percent. Piping System: Ordinary entrance, 10 feet of horizontal 4" sch 40 pipe, pump, open gate valve, 80 feet of 3" sch 40 pipe plus 2 elbow and an open check valve, into the pressure vessel. The level in the pressure vessel is 20 feet above the level in the storage tank. Assume that the benzene enters the pressure vessel below the level of liquid in the vessel. Assume benzene density is 54 lbs/ft³.
2. You are a project engineer for a pipe-line company. A 20-mile-long pipeline delivers petroleum at a rate of 5000 barrels per day. The resulting pressure drop is 500 psi. If a parallel line of the same size is laid along the last 11 miles of the line, what will be the new capacity of this network? Flow in both cases is laminar and the overall pressure drop remains 500 psi.
3. You are a process development engineer for a synthetic plastics company. A process requires the development of a heat transfer device. A fluid is to be heated in a double-pipe heat exchanger. The fluid is flowing inside a 1-inch sch 40 steel pipe with a velocity of 1 ft/sec. The fluid is to be heated in the pipe from 100°F to 160°F. The annular space between the pipes contains steam condensing at 200°F. The heat-transfer coefficient for condensing steam is 2000 Btu/hr ft²°F. The fluid has the following

average physical properties:

density	— 56 lbs/ft ³
specific heat	— 0.47 Btu/lb°F
thermal conductivity	— 0.07 Btu/hr ft°F
viscosity	— 4.0 cps

Find the length of pipe required for the exchanger.

4. You are a tired and puzzled student in ChE 305 (the real you?). The professor puts the following crazy question on the final exam. (Don't panic this is a relatively easy problem, just read carefully.)

The circulation of blood in the finger maintains a temperature of 98.6°F at a short distance, say 1/8 inch, below the surface of the skin. The nerve endings, which are temperature indicators, are 1/16 inch below the surface of the skin, your distress is considered to be noticeable when the nerve endings attain a temperature of 110°F. Using these criteria, find the maximum temperature of water in which you could hold your finger. Assume the system is adequately modeled as a flat plate.

Thermal conductivity of flesh and blood	— 0.35 Btu/hr ft°F
Convective coefficient for finger dipped in water	— 100 Btu/hr ft ² °F

1 ft ³ contains	7.48 gallons
1 H.P. =	550 ft-lb _t /sec
1 bbl =	42 gallons

ChE books received

"Advances in Cryogenic Engineering" Vol 3. Edited by K. D. Timmerhaus, Plenum Press, New York. pp 747, 1978. \$49.50

This is the proceedings of the 1977 Cryogenic Engineering Conference held at the University of Colorado, Boulder, CO. Papers include superconductivity applications, heat transfer, mass transfer, cryogenic techniques and applications, and LNG design and properties.

"Applied Cost Engineering" by F. D. Clark and A. B. Lorenzoni. Marcel Dekker, Inc., New York. pp 297, 1978. \$24.50

This is the first in a series of reference books and textbooks on cost engineering. It is concerned with cost estimation and cost control and does not discuss engineering economics, the third area of cost engineering. The authors include few specific data but give the reader basic philosophy and ideas for developing his own data, estimating method or cost control system.

"A Programmed Review of Engineering Fundamentals" by A. J. Baldwin and K. M. Hess. Van Nostrand Reinhold, New York. pp 287, 1978. \$18.95

This programmed text is for anyone preparing for the National Engineering Fundamentals Examination. The text includes review material in mathematics and science and engineering fundamentals.

Continued on page 52

ChE letters

CITATIONS CORRECTION

Dear Sir:

In the Fall issue of *CEE* Professors Carbonell and Whitaker identified the origin of the method of volume averaging as a pair of independent papers by Slattery (1967) and Whitaker (1967). That citation unfortunately overlooked the work of Anderson and Jackson (1967) who also derived the spatial averaging theorem independently and used the result to analyze motion in a fluidized bed.

Anderson, T. B. and R. Jackson, "A Fluid Mechanical Description of Fluidized Beds", *I.E.C. Fund* 6, 527 (1967)

Slattery, J. C., "Flow of Viscoelastic Fluids Through Porous Media", *AIChE* 13, 1066 (1967)

Whitaker, S., "Diffusion and Dispersion in Porous Media," *AIChE Journal* 13, 420 (1967)

Stephen Whitaker
Visiting Professor
University of Houston

CONFERENCE ON CASE STUDIES

Editor:

Please publish the following announcement:

"National Conference on Case Studies in Engineering Education" sponsored by the ASEE Engineering Case Committee, March 28-30, 1979, Columbia, South Carolina. Topics: Preparation, writing, and use of case studies; application of cases to instruction in specific engineering disciplines; case use in legal, political, ethical, and economic aspects of engineering. Papers dealing with these topics will be published in a Proceedings which will be available at the conference. For information, contact the Office of Continuing Engineering Education, University of South Carolina, Columbia, South Carolina 29208; telephone 803-777-6693

Tim A. Jur
Conference Chairman

CALL FOR PAPERS

Dear Sirs:

The Irish Branch of the Institution of Chemical Engineers is organizing an International Conference on Solids Separation Processes to be held in Dublin in April 1980 in association with the Annual General Meeting of the Institution.

The Conference Organizing Committee is inviting papers for the conference and would be pleased if you could give some prominence to the "Call for Papers" in your journal.

Abstracts should be sent, as soon as possible, but not later than April 1, 1979, to

Dr. John J. Kelly, Chairman, Tech. Com.
Intern. Conf. on Solid's Sep. Processes
BeMRA
Tramway House, Dartry Road
Dublin 6, Ireland

D. J. Menzies
Conference Secretary

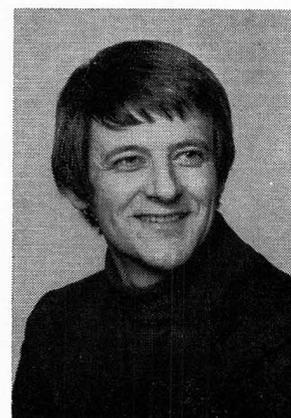
AN ENTRANCE REGION MASS TRANSFER EXPERIMENT

G. R. YOUNGQUIST
Clarkson College of Technology
Potsdam, New York 13676

PART OF CLARKSON'S undergraduate laboratory course is devoted to experiments which reinforce concepts introduced in earlier lecture courses. This paper describes an experiment designed to reveal the consequences of the development of a concentration boundary layer. The rate of a mass transfer limited electrochemical reaction is measured and used to obtain the dependence of average Sherwood number on Reynolds number and entrance length. The experimental results may be compared directly to theory for laminar flows and to existing correlations for turbulent flows.

When a fluid enters a section of conduit where mass is exchanged between the fluid and the conduit wall, the concentration profile in the fluid undergoes rapid change. An initially flat profile changes to one exhibiting a large concentration gradient at the wall. The shape of the concentration profile in the fluid leaving a mass transfer section will depend on the length of the section until, for sufficiently long sections, the profile becomes fully developed. As a consequence of the development of the profile, the local mass transfer coefficient decreases from a large value at the leading edge of the mass transfer section to a minimum downstream. Correspondingly, the average mass transfer coefficient decreases with increasing length for the mass transfer section. Dependence

This experiment is simple to carry out in the laboratory, and a large amount of good data can be obtained in a relatively short period of time.



Gordon Youngquist received his BS from the University of Minnesota and his MS and PhD from the University of Illinois. Since 1962 he has been at Clarkson College of Technology where his teaching and research interests are in reactor analysis, crystallization and porous media.

of the mass transfer coefficient on system properties and conditions is normally described as

$$Sh_{Avg.} = f\left(Re, Sc, \frac{d_e}{L} \right)$$

where

$$Sh_{Avg.} = \frac{k_{Avg.} d_e}{D}; Re = \frac{d_e \langle v \rangle}{\nu}; Sc = \frac{\nu}{D}$$

and

- $k_{Avg.}$ = average mass transfer coefficient
- D = diffusivity
- ν = kinematic viscosity
- d_e = equivalent diameter
- $\langle v \rangle$ = average velocity
- L = mass transfer length

For laminar flow between flat plates, Leveque

analysis (Newman, 1968; Newman, 1973) gives

$$Sh_{AVG.} = 1.85 \left(\frac{ReScd_e}{L} \right)^{1/3} \quad (1)$$

For turbulent flow in circular tubes, Van Shaw, et al. (1963) give

$$Sh_{AVG.} = 0.276 Re^{0.58} Sc^{1/3} \left(\frac{d_e}{L} \right)^{1/3} \quad (2)$$

Electrode reactions have often been used for experimental determination of forced convection mass transfer rates in solution (Lin, et al. 1951; Van Shaw et al., 1963; Eisenberg, et al., 1955). Some of the various reactions used are:

- 1.) Reduction of ferricyanide ion
 $Fe(CN)_6^{-3} + e \rightarrow Fe(CN)_6^{-4}$
- 2.) Reduction of quinone
 $C_6H_4O_2 + 2H^+ + 2e \rightarrow C_6H_4(OH)_2$
- 3.) Reduction of oxygen
 $O_2 + 4e + 2H_2O \rightarrow 4OH^{-1}$
- 4.) Oxidation of ferrocyanide ion
 $Fe(CN)_6^{-4} \rightarrow Fe(CN)_6^{-3} + e$

Such reactions involve two steps: mass transfer of reactants from the bulk solution to the surface of the electrode and reaction at the electrode. At low cell potentials, the reaction rate is reaction limited. As the cell potential is increased, the rate increases to the point where it is mass transfer limited, the concentration of reactant at the electrode surface is essentially zero, and the limiting cell current is attained. Under these conditions, the mass transfer rate is given by

$$k_{AVG.} A C_{CO} = \frac{i_L}{nF} \quad (3)$$

where

- A = electrode area
- C_{CO} = bulk reactant ion concentration
- i_L = limiting cell current
- F = Faraday's constant
- n = number of electrons per ion reacted at the electrode

This paper describes an experiment designed to reveal the consequences of the development of a concentration boundary layer. The rate of a mass transfer limited electrochemical reaction is measured and used to obtain the dependence of average Sherwood number on Reynolds number and entrance length.

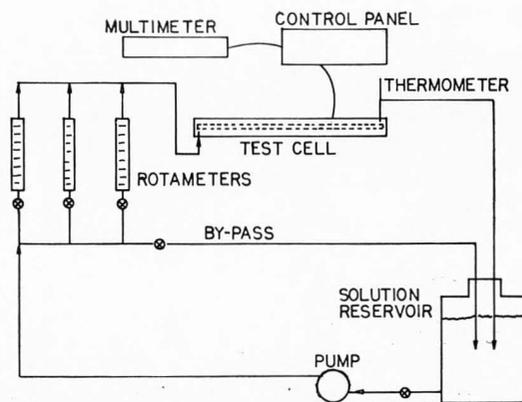
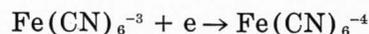


FIGURE 1. Schematic Diagram of Apparatus

By measuring the limiting current and knowing the bulk reactant concentration and the electrode area, the average mass transfer coefficient may be calculated.

APPARATUS AND TECHNIQUES

REDUCTION OF FERRICYANIDE ion in a sodium hydroxide solution on a nickel cathode is used to measure mass transfer rates in our experiment:



The apparatus, shown schematically in Figure 1, consists of a rectangular duct through which $Fe(CN)_6^{-3}/Fe(CN)_6^{-4}/NaOH$ solution is circulated. Current is passed between the test electrodes using a 6 volt storage battery as the D.C. source. A ten-turn potentiometer is provided for cell voltage control. Current and voltage in the test section are measured with a digital multimeter. Rotameters are provided for flow measurement. PVC pipe was used for connecting lines and valves and pump body were of stainless steel.

The test cell, mounted horizontally, is made of Plexiglas with a duct 0.635 cm \times 2.86 cm in cross-section and approximately 125 cm in length. Six cathodes (0.635, 1.27, 1.91, 2.54, 3.81 and 5.08 cm \times 2.86 cm) are provided. Oxidation of ferrocyanide ion takes place at a large anode (30 \times 2.86 cm) placed opposite to the cathodes. The electrolyte solution contains equimolar amounts of potassium ferricyanide and ferrocyanide (about 0.015 molar). Approximately 2 M. NaOH is used as an indifferent electrolyte to eliminate ionic migration effects.

To determine the limiting current, and hence the mass transfer coefficient, steady flow at a de-

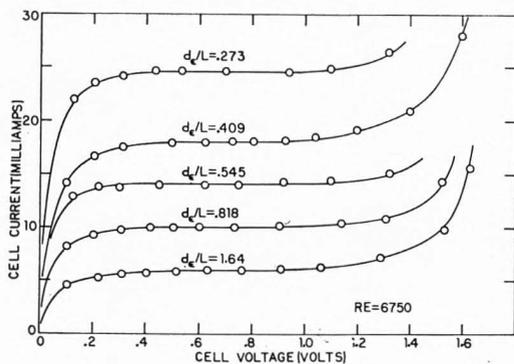


FIGURE 2. Data for Determination of Limiting Current

sired rate through the test section is established. Then, the cell current is measured as a function of applied cell voltage for a given cathode. The procedure is repeated for each cathode and over the maximum flow rate range possible.

Additional details concerning the apparatus and procedures are appended.

RESULTS

FIGURE 2 SHOWS cell current vs cell voltage data acquired for determination of limiting current for several electrodes at constant flow rate. Some care must be taken to clean and activate the electrodes properly and to avoid dissolved oxygen (see Appendix) or the limiting current will not be well defined. It is apparent that the limiting current is attained for each of the electrodes in the cell voltage range 0.4-1.0 volts. Similar behavior is observed at various flow rates. Once this cell voltage range has been determined, limiting current data may be obtained quickly for the various electrodes and flow rates without changing the cell voltage. The rapid increase of the current at high voltages is caused by a second electrode reaction which results in hydrogen evolution. Naturally, the data of interest are in a cell

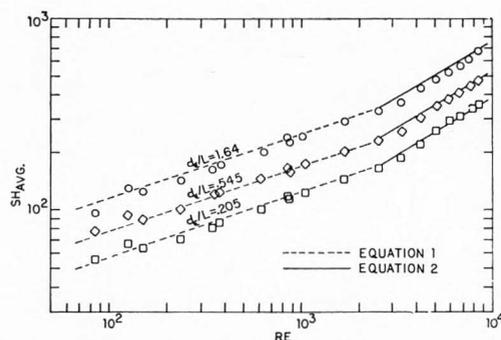


FIGURE 3. Dependence of Average Sherwood Number on Reynolds Number

voltage range below the point where this reaction becomes of importance.

From the limiting current, the average mass transfer coefficient may be calculated by rearrangement of Equation 3 according to

$$k_{\text{AVG.}} = \frac{i_L}{nFAc_{\infty}}$$

These data then may be compared to the predictions of Equations 1 and 2. For calculation of the Sherwood number, the diffusivity of ferricyanide ion is necessary. Van Shaw, et al. (1963) give a value of 5.2×10^{-6} cm²/sec. Alternatively, the dif-

The experimental results here provide clear confirmation of several qualitative cause-effect relationships commonly used in introducing boundary layer theory.

fusivity might be estimated from the Nernst equation:

$$D = \frac{RT\lambda_1^{\circ}}{Z_1F^2}$$

where

λ_1° = equivalent conductance at infinite dilution

Z_1 = ion valence

For calculation of the Reynolds number and Schmidt number, the kinematic viscosity also is needed and is easily determined by experiment.

Figure 3 depicts laboratory data for the dependence of average Sherwood number on Reynolds number for several electrode lengths. Transport properties used for calculation are

$$D = 5.2 \times 10^{-6} \text{ cm}^2/\text{sec} \text{ (Van Shaw, et al., 1963)}$$

$$\nu = 8.1 \times 10^{-3} \text{ cm}^2/\text{sec} \text{ (determined experimentally @ 31}^{\circ}\text{C)}$$

Figure 4 shows data for the dependence of average Sherwood number on entrance length. The transition from laminar flow appears clearly as a change in slope on the Reynolds number plot at $Re \approx 2400$, and the Sherwood number decreases with length as anticipated. The lines through the data on each figure represent the predictions of Equations 1 and 2. The agreement between experiment and prediction is very good. The good agreement with Equation 2 is somewhat surprising since the corresponding experimental data were

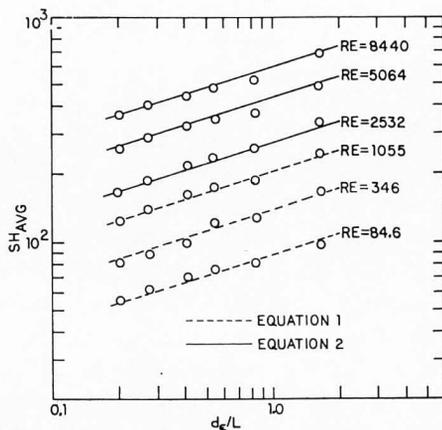


FIGURE 4. Dependence of Average Sherwood Number on Entrance Length

all in the transition region. The average deviation is 4.9% for the laminar flow data (72 data points) and 5.9% for the turbulent flow data (48 data points).

The data also were correlated using a least squares technique. Using the functional form of Equations 1 and 2,

$$Sh_{AVG} = aSc^bRe^c \left(\frac{d_e}{L} \right)^d \quad (4)$$

where a , b , c , and d are unknown constants. Linearizing,

$$\ln(Sh_{AVG}) = \ln(a) + b \ln(Sc) + c \ln(Re) + d \ln \left(\frac{d_e}{L} \right) \quad (5)$$

Since it was not feasible to vary the Schmidt number experimentally, Equation 5 is of the form

$$y = A + cx_1 + dx_2 \quad (6)$$

where

$$\begin{aligned} y &= \ln(Sh_{AVG}) \\ A &= \ln(a) + b \ln(Sc) \\ x_1 &= \ln(Re) \\ x_2 &= \ln \left(\frac{d_e}{L} \right) \end{aligned}$$

Good agreement of experimental data with the predictions of theory and/or existing correlations is often satisfying to the students, although most tend to need considerable guidance in examining the data.

Using least squares, best values of A , c , and d were determined from the data, separately for the laminar and turbulent flow ranges. The results were

$$Sh_{AVG} = 20.1 Re^{0.336} \left(\frac{d_e}{L} \right)^{0.317} \quad \text{for laminar flow} \quad (7)$$

and

$$Sh_{AVG} = 1.94 Re^{0.628} \left(\frac{d_e}{L} \right)^{0.291} \quad \text{for turbulent flow} \quad (8)$$

which compare favorably with Equations 1 and 2. Using these correlations, the average deviations

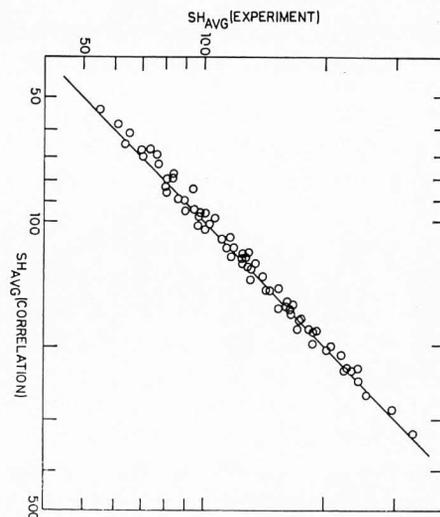


FIGURE 5. Comparison of Experimental Data with Correlation (Laminar Flow)

are 3.5% and 3.6% for laminar and turbulent flow, respectively. The results of the correlation are shown in Figures 5 and 6.

DISCUSSION

THIS EXPERIMENT IS simple to carry out in the laboratory, and a large amount of good quality data can be obtained in a relatively short period of time. (The data shown in this paper were obtained in about three hours.) Students tend to find the data acquisition somewhat boring, since this largely consists of reading the rotameter and multimeter while making occasional valve and potentiometer adjustments. The real challenge lies in developing some understanding of the physics implicit in the data and in doing the data correlation.

For many students, the notions of boundary

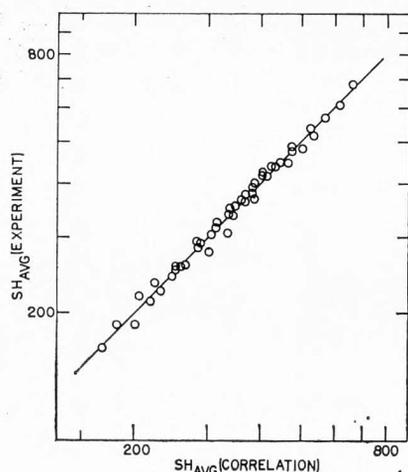


FIGURE 6. Comparison of Experimental Data with Correlation (Turbulent Flow)

layer development are difficult to grasp. The experimental results here provide clear confirmation of several qualitative cause-effect relationships commonly used in introducing boundary layer theory. Good agreement of experimental data with the predictions of theory and/or existing correlations is often satisfying to the students, although most tend to need considerable guidance in examining the data. Exposure to an electrochemical reaction is educationally useful. Moreover, the transition from reaction control to mass transfer control observed in determining the limiting current reinforces the importance of mass transfer to many chemically reacting systems.

The equipment has been relatively maintenance free, although some difficulty was experienced initially in finding a suitable technique for bonding the nickel electrodes to the Plexiglas duct. Prolonged exposure to the NaOH solution being

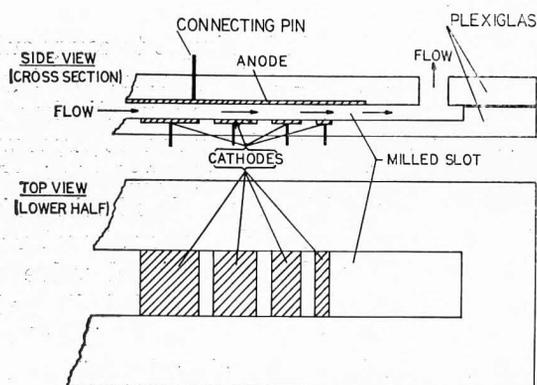


FIGURE 7. Detail of Test Cell Construction

circulated tends to weaken the adhesive bond of many cements. Flushing the duct with water after each use minimizes this effect. Care must be taken to keep the electrodes clean and properly activated (see Appendix) or the limiting current will be ill-defined. This may require occasional disassembly of the duct. Bubbling nitrogen into the feed storage tank for several hours prior to the start of the experiment serves to remove dissolved oxygen, another cause of an ill-defined limiting current. The electrolyte solution is stable, provided direct exposure to ultraviolet light which catalyzes decomposition reactions of the cyanides is avoided. Use of an opaque feed tank and plumbing and flushing the Plexiglas duct and rotameters after use solves the problem. Fresh electrolyte solution is normally prepared but once per semester. Con-

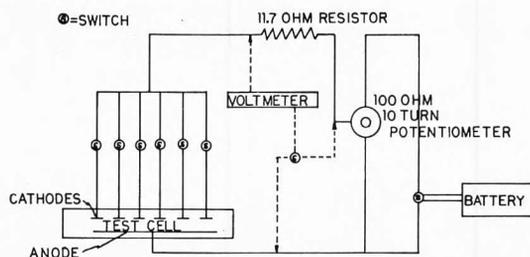


FIGURE 8. Schematic of Control and Measuring Circuit

centrations are checked periodically using iodometric analysis for ferricyanide and permanganate titration for ferrocyanide (Kolthoff and Sandell, 1952). Ordinarily these concentrations do not change significantly over the course of a semester.

ACKNOWLEDGMENT

THE ASSISTANCE OF Professor Der-Tau Chin who suggested the experiment and Mr. Peter Clark who did the data correlation is gratefully acknowledged.

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APPENDIX

Test Cell Assembly: The test cell was made from two pieces of 1/2 inch Plexiglas sheet approximately 10 x 125 cm (4 x 48 inches) as detailed in Figure 7. A slot 0.635 cm deep x 2.86 cm wide (1/4 x 1 1/8 inches) was milled in one piece to form the flow duct. 22 gage nickel sheet was used for the electrodes which covered the width of the duct. Each piece of Plexiglas was additionally milled to accommodate the thickness of the electrodes (secured using "Krazy Glue") so that a smooth flow channel was obtained. Electrical connecting pins were made by silver soldering a small brass machine screw to the back side of each electrode. The access hole through the Plexiglas for each pin was backfilled using Epoxy Cement. The halves of the cell were bolted together using Parafilm sheet as a gasket.

Some considerable care must be taken in attaching the cell electrodes. Many glues do not provide a strong adhesive bond between the nickel electrodes and the Plexiglas which is also resistant to attack by NaOH. Flushing the cell with water after use extends the useful life of the bond.

After attaching the electrodes and before bolting the cell together, the electrodes should be cleaned and activated. The electrode surfaces should be polished with fine emery cloth, followed by washing with detergent. To activate the electrodes, the test section is placed in approximately 2 M NaOH solution. A cell formed using a strip of nickel as the anode and each electrode in turn as the cathode is connected to a 6 volt D.C. source for 4 to 5 minutes. Caution should be used, as hydrogen evolution is considerable. Finally, the test section is rinsed with distilled water and the cell assembled.

Control and Measuring Circuit: A schematic of the control and measuring circuit is given in Figure 8. The cell voltage and current were determined using a digital voltmeter which could be switched alternately to measure the voltage drop across the cell and across a standard resistor placed in series with the cell. The cathodes were wired in parallel with an isolating switch for each. A 6 volt storage battery was used as the power source, and cell voltage was controlled using a 100 ohm, 10-turn potentiometer. □

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WHAT IS CHEMICAL STOICHIOMETRY?

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A CONSIDERABLE AMOUNT OF literature has arisen in recent years [1-21], which, based on earlier work [22-29], has focussed on the utility of the description of the stoichiometry of closed, chemical systems in terms of linear algebra. This utility, however, does not seem to be appreciated as widely as it should be.* This may be partly because the treatments mostly involve stoichiometry as it impinges on other fields, such as kinetics and thermodynamics, with possibly some resulting confusion over terminology and the nature of the basic questions being resolved by stoichiometry itself.

Here we focus on chemical stoichiometry, *per se*, in a treatment free from kinetic or thermodynamic considerations, in order to focus on these basic questions and their answers. Specifically we provide a means for determining the following:

- the number of stoichiometric degrees of freedom, which is the same as the number of independent chemical equations
- the number of components
- a permissible set of chemical equations, and
- a permissible set of components,

for a closed system undergoing chemical reaction, which includes allowance for mass transfer between phases. The treatment allows for the presence of inert species and charged species.

It is first necessary to justify the questions and provide unambiguous terminology. The method is then presented and illustrated with several examples.

CHEMICAL STOICHIOMETRY

WE MAY DEFINE CHEMICAL stoichiometry as the constraints placed on the composition

*For example, the Chemical Engineers' Handbook [30] has short sections on matrices [30a] and on solutions of linear equations [30b], but the applications mentioned for the former do not include chemical stoichiometry.

of a closed, chemical system by the necessity of conserving the amount of each elemental or atomic species in any physicochemical change in state occurring within the system. These constraints take the form of conservation equations. The difference between the number of variables (e.g., relative mole numbers of species in a basis amount of system) used to describe the composition and the number of such conservation equations may be called the number of stoichiometric degrees of freedom, denoted by F_s . This is then the number of pieces of information or relations among the variables required to determine completely any compositional state from a given one. These pieces of information or relations may come from analytical determinations or from kinetic rate laws or from equilibrium constraints, but, apart from the num-



William R. Smith received his university degrees from Toronto (B.A.Sc., M.A.Sc.) in ChE and from Waterloo (M.Sc., Ph.D.) in applied mathematics. His main research interests are in statistical mechanics, thermodynamics, and biomathematics. He has published 41 papers in these areas. He is an associate professor of Mathematics at Dalhousie University and holds a joint appointment in the Department of Physiology and Biophysics. (L)

Ronald W. Missen is a Professor in the Department of ChE and Applied Chemistry at the University of Toronto, where he has been since 1956, and Vice-Provost (Professional Faculties) in the University. He received B.Sc and M.Sc. degrees in ChE from Queen's University, Kingston, Ontario, in 1950 and 1951, respectively, and a Ph.D. in physical chemistry from the University of Cambridge, Cambridge, England, in 1956. From 1951 to 1953 he was with Polysar Corporation in Sarnia, Ontario. He spent the year 1967/68 on sabbatical leave at the University of California, Berkeley. His research and teaching interests are mainly in thermodynamics and in chemical reactor behaviour. (R)

ber required, they are outside the scope of stoichiometry. The determination of F_s depends only on the basic concept of conservation of atomic species, and is independent of other concepts and descriptive features, including temperature, pressure, uniformity of a phase, whether or not a system is at equilibrium, and the nature and mechanism of reactions actually taking place.

The stoichiometric description of a chemical system may be in terms of algebraic atom-balance equations, or, more familiarly, in terms of chemical equations. Chemical stoichiometry also enables us to determine the number (R) of such chemical equations and to write a permissible set of them in terms of the reacting species involved. It is important to see the connection between the atom-balance equations and the chemical equations, and this is treated below.

Whether or not chemical equations are used, it is convenient to divide the reacting species into two groups: components and non-components (the latter are sometimes [21] referred to as key components). In terms of chemical equations, the components may be viewed as the "building blocks" for formation of the non-components, one equation being required for each non-component. The minimum number of such building blocks that must be available in order that any compositional state of the system can be realized is the number of components C . Chemical stoichiometry enables us to determine C and a permissible set of components from the species making up the system.

TERMINOLOGY

We define the following terms:

Chemical species: a chemical entity distinguishable from other such entities by (1) its molecular formula; or failing that, by (2) its molecular structure (e.g., to distinguish isomeric forms with the same molecular formula); or failing that, by (3) the phase in which it occurs (e.g., $H_2O(l)$ is a species distinct from $H_2O(g)$); the number of species is N

Chemical substance: a chemical entity distinguishable by (1) or (2) above, but not by (3); thus $H_2O(l)$ and $H_2O(g)$ are the same substance, water

Chemical system: a collection of chemical species and elements denoted by an ordered set of species and an ordered set of the elements contained therein as follows: $[(A_1, A_2, \dots, A_N), (E_1, E_2, \dots, E_k, \dots, E_M)]$, where A_i is the molecular formula, together with structural and phase designations, if necessary, of species i , and E_k is element k ; the list of elements includes (1) each isotope involved in isotopic exchange, (2) the protonic charge, p , if ionic species are involved, and (3) a designation, such as X_1, X_2, \dots , for each inert substance in the species list, an inert substance being one

We may define chemical stoichiometry as the constraints placed upon the composition of a closed, chemical system by the necessity of conserving the amount of each elemental or atomic species in any physicochemical change in state occurring within the system.

that is not involved in the system in the sense of physicochemical change; the number of elements is M

Formula vector [25], a_i : the vector of subscripts to the elements in the molecular formula of a species; e.g., for $C_6H_5NO_2$, $a = (6, 5, 1, 2)^T$; in what follows, all vectors are column vectors and superscript T denotes the transpose of a vector

Formula-vector matrix, A : the $M \times N$ matrix in which column i is a_i ; $A = (a_1, a_2, \dots, a_i, \dots, a_N)$; A is also the coefficient matrix in the element-balance equations $\sum_i a_{ki} n_i = b_k$; $k = 1, 2, \dots, M$ (see equ. (1), below), where a_{ki} is the subscript to the k th element in the molecular formula of species i

Species-abundance vector, n : the vector of non-negative real numbers representing the numbers of moles of the species in a basis amount of the chemical system; $n = (n_1, n_2, \dots, n_i, \dots, n_N)^T$; $n_i \geq 0$

Element-abundance vector, b : the vector of non-negative real numbers representing the numbers of moles of elements in a basis amount of the chemical system; the element-balance equations may be written as $An = b$; b is often specified by the relative amounts of "reactants" for the system

Closed chemical system: one for which all possible n satisfy the element-balance equations for some given b

Species-abundance-change vector, $\delta n = n^{(2)} - n^{(1)}$: the changes in mole numbers between two states of the closed chemical system; it must satisfy $A\delta n = 0$

Feasibility or infeasibility of a closed chemical system refers to whether or not a given b is compatible with the species list; e.g., for the system $[(H_2O, H_2, O_2), (H, O)]$; $b = (b_H, b_O)^T$, $b = (3, 2)^T$ is feasible, but $b = (3, 0)^T$ is infeasible; a necessary condition for feasibility is that the rank of the augmented matrix (A, b) , obtained from the system of linear equations $An = b$, be equal to the rank of A ; this is not a sufficient condition because the algebraic theorem on which it is based allows for the possibility of solutions involving negative values for some or all of the n_i ; a sufficient condition for infeasibility is that the ranks be unequal; we assume in what follows that all systems are feasible

ATOM-BALANCE EQUATIONS AND CHEMICAL EQUATIONS

In a closed system, the conservation of atomic species can be expressed in a set of atom-balance equations, one for each element:

$$\sum_{i=1}^N a_{ki} n_i = b_k; k = 1, 2, \dots, M. \quad (1)$$

In vector-matrix notation, this is

$$\mathbf{A}\mathbf{n} = \mathbf{b}. \quad (1a)$$

These equations may alternately be written so as to express the change from one compositional state to another. Thus in a closed system,

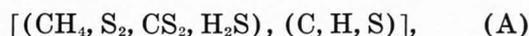
$$\sum_{i=1}^N a_{ki} \delta n_i = 0; k = 1, 2, \dots, M, \quad (2)$$

or

$$\mathbf{A}\delta\mathbf{n} = \mathbf{0}. \quad (2a)$$

The maximum number of linearly independent atom-balance equations, which is the same as the maximum number of linearly independent rows (or columns) in the matrix \mathbf{A} , is given by the rank of \mathbf{A} [31].

Before giving the general description, we use an example to illustrate these relations and the connection between them and chemical equations, and also the ideas of components, non-components, and stoichiometric degrees of freedom. Consider first then a closed, reacting system made up of the given species CH_4 , S_2 , CS_2 and H_2S . Formally, this is represented as



where the first set is that of the species, arbitrarily ordered as indicated, and the second set is that of the elements, also arbitrarily ordered.

The atom-balance equations (1) are, for the species and the elements in the order chosen, and with subscripts 1, 2, 3 and 4 referring to CH_4 , S_2 , CS_2 and H_2S , respectively.

$$\begin{aligned} 1 n_1 + 0 n_2 + 1 n_3 + 0 n_4 &= b_{\text{C}}, \\ 4 n_1 + 0 n_2 + 0 n_3 + 2 n_4 &= b_{\text{H}}, \\ \text{and } 0 n_1 + 2 n_2 + 2 n_3 + 1 n_4 &= b_{\text{S}}. \end{aligned}$$

For a given \mathbf{b} , we have three equations in four unknowns. We expect to be able to solve for any three n 's in terms of the fourth; that is, we have one degree of freedom. Suppose we have one particular solution of these equations (e.g., one corresponding to an initial state), $\mathbf{n}^* = (n_1^*, n_2^*, n_3^*, n_4^*)^T$. For a change from this state to any other state, with composition \mathbf{n} , on rewriting the above equations in terms of \mathbf{n}^* , and subtracting one set from the other, we have

$$\left. \begin{aligned} 1\delta n_1 + 0\delta n_2 + 1\delta n_3 + 0\delta n_4 &= 0, \\ 4\delta n_1 + 0\delta n_2 + 0\delta n_3 + 2\delta n_4 &= 0, \\ \text{and } 0\delta n_1 + 2\delta n_2 + 2\delta n_3 + 1\delta n_4 &= 0, \end{aligned} \right\} (\text{B})$$

where $\delta n_i = n_i - n_i^*$, etc.

The first of these, for example, states that the

amount of carbon in the closed system is fixed ($\delta n_{\text{C}} = 0$), regardless of how much chemical change occurs. The second and third refer similarly to hydrogen and sulfur, respectively.

The matrix \mathbf{A} for this system is

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 4 & 0 & 0 & 2 \\ 0 & 2 & 2 & 1 \end{bmatrix}, \quad (\text{C})$$

where the columns are the formula vectors for the species in the order given in specification (A).

Equations (B) can be rearranged to solve for any three δn 's in terms of the fourth, e.g., δn_1 , δn_2 and δn_3 in terms of δn_4 . To accomplish this we reduce \mathbf{A} to unit matrix form [31a] by elementary row operations [31b]. The "unit matrix form" is represented by [31a]

$$\mathbf{A}^* = \begin{bmatrix} \mathbf{I}_C & \mathbf{Z} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \quad (3)$$

where \mathbf{I}_C is a ($C \times C$) unit matrix, and \mathbf{Z} is a ($C \times (N - C)$) matrix whose elements may be nonzero. The number C is the rank of \mathbf{A} and of \mathbf{A}^* . The procedure in general is similar to that used in the solution of linear algebraic equations by Gauss-Jordan reduction [31c]. In this particular case, we obtain eventually a matrix \mathbf{A}^* given by

$$\mathbf{A}^* = \begin{bmatrix} 1 & 0 & 0 & \frac{1}{2} \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & -\frac{1}{2} \end{bmatrix}. \quad (\text{D})$$

Here the unit matrix is (3×3) and the rank of \mathbf{A} is then 3.

Equation (D) implies that equations (B) can be written

$$\left. \begin{aligned} \delta n_1 &+ \frac{1}{2}\delta n_4 = 0, \\ \delta n_2 &+ \delta n_4 = 0, \\ \text{and } \delta n_3 &- \frac{1}{2}\delta n_4 = 0. \end{aligned} \right\} (\text{E})$$

In other words the mole-number changes for reaction involving these species can all be related by stoichiometry to one mole-number change, such as that for H_2S , as indicated.

Alternatively we may write Equations (E) as

**The stoichiometric description
of a chemical system may be in terms
of algebraic atom-balance equations, or, more
familarly, in terms of chemical equations.**

$$\frac{\delta n_4}{+1} = \frac{\delta n_1}{-1/2} = \frac{\delta n_2}{-1} = \frac{\delta n_3}{+1/2}.$$

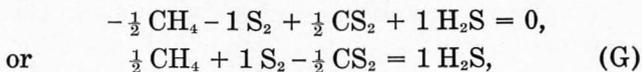
Setting these quantities equal to a parameter ξ , and substituting for δn_1 , etc. in equations (B), we obtain

$$\begin{aligned} 1(-1/2)\xi + 0(-1)\xi + 1(1/2)\xi + 0(1)\xi &= 0, \\ 4(-1/2)\xi + 0(-1)\xi + 0(1/2)\xi + 2(1)\xi &= 0, \\ 0(-1/2)\xi + 2(-1)\xi + 2(1/2)\xi + 1(1)\xi &= 0, \end{aligned}$$

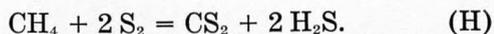
and

$$\begin{aligned} \text{or } -\frac{1}{2} \begin{bmatrix} 1 \\ 4 \\ 0 \end{bmatrix} \xi - 1 \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} \xi + \frac{1}{2} \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix} \xi + \\ 1 \begin{bmatrix} 0 \\ 2 \\ 1 \end{bmatrix} \xi &= \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \end{aligned} \quad (\text{F})$$

And replacing each vector in (F) by the corresponding molecular formula, we have



or, as we would usually write,



We thus see that a chemical equation is a shorthand way of writing equation (F). Note that the coefficients of the species on the left side of equation (G) are contained in the last column of matrix A^* in equation (D). Equation (G) is written as though these species are the (three) components or building blocks for the formation of one mole of the non-component H_2S . The components are thus the species represented by the columns in the unit matrix of A^* , the non-component is the species represented by the remaining column apart from the unit matrix, and the coefficients in equation (G) are given in the order (down the last column) in which the components are represented in the first three columns.

(The technique described in this example leading to equations (D) and (G) can also be used to balance an oxidation-reduction equation in inorganic-analytical chemistry, as an alternative to methods such as the half-reaction method using oxidation numbers [32], and analogous ion-electron and valence-electron methods [33], which require additional concepts.)

A slightly more involved system results if we add H_2 to our species list contained in (A). We now have five δn 's in the three equations corresponding to (B). An additional column is added

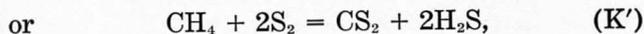
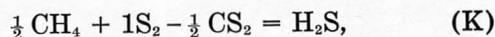
to matrix A, which becomes

$$A = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 \\ 4 & 0 & 0 & 2 & 2 \\ 0 & 2 & 2 & 1 & 0 \end{bmatrix}. \quad (\text{I})$$

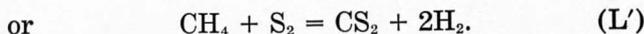
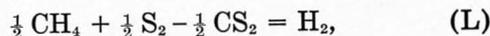
By means of elementary row operations, this can be reduced to

$$A^* = \begin{bmatrix} 1 & 0 & 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & 1 & 0 & 1 & \frac{1}{2} \\ 0 & 0 & 1 & -\frac{1}{2} & -\frac{1}{2} \end{bmatrix}. \quad (\text{J})$$

Again the rank of the matrix is 3, which is the number of components C. The same set of components can be used, CH_4 , S_2 and CS_2 . The difference is that there are now two columns apart from the unit matrix, which implies two independent mole number changes, or stoichiometric degrees of freedom ($F_s = 2$), or chemical equations ($R = 2$). The matrix form (J) provides a solution for each of δn_1 , δn_2 and δn_3 in terms of δn_4 and δn_5 . Alternatively, it provides the stoichiometric coefficients for the two equations in which one mole of each of the two non-components is "formed" in turn from the three components. Thus from column 4 of (J) for H_2S , as before, we obtain



and from column 5 for H_2 , we obtain similarly



Equations (K') and (L') can be said to represent the stoichiometry of this (five-species) reaction system. However, they are not unique; any linear combination of them can be used to replace either one. They carry no necessary implications about the mechanism of reaction(s) occurring, or about "reactants" or "products".

In these two examples no column interchanges were required to obtain the unit matrix form (3). This is because in each case the arbitrary ordering of species was such that the first three (CH_4 , S_2 , CS_2) formed a permissible set of components, satisfying the necessary condition that each element be contained in at least one molecular formula. If this is not the case, it will be automatically taken care of by the requirement of column interchange(s) to arrive at the unit matrix form (3). For example, in the second case, if the species were arbitrarily ordered as H_2 , S_2 , H_2S , CS_2 , CH_4 , the

first three would not form a permissible set of components, since the element C is missing. The procedure provided here would, however, reorder the species automatically by column interchange to provide a permissible set in the unit matrix.

GENERAL TREATMENT

Equations (1) or (1a) are a set of M linear algebraic equations in N unknowns \mathbf{n} for given \mathbf{b} . The general solution of this set of equations may be written

$$\mathbf{n} = \mathbf{n}^* + \sum_{j=1}^R \nu_j \xi_j, \quad (4)$$

where \mathbf{n}^* is any particular solution of equations (1); ν_j , $j = 1, 2, \dots, R$, are a set of linearly independent solutions of the corresponding homogeneous equations (2); and ξ_j are a set of arbitrary real numbers. The number R is given by

$$R = N - \text{Rank}(\mathbf{A}), \quad (5)$$

and is the maximum number of linearly independent solutions of equations (2).

The chemical significance of equation (4) is that any compositional state of the system \mathbf{n} , can be written in terms of any particular state \mathbf{n}^* and a linear combination of a set of R linearly independent vectors ν_j obeying equations (2) or (2a).

Equation (4) leads naturally to the concept of chemical equations. To show this, we first use the fact that the vectors ν_j in equation (4) are solutions of equations (2a) and write

$$\mathbf{A}\nu_j = 0; j = 1, 2, \dots, R. \quad (6)$$

A convenient way of writing all R such equations at once is by defining a matrix \mathbf{N} whose columns are the vectors ν_j ; that is,

$$\mathbf{N} = (\nu_1, \nu_2, \dots, \nu_R). \quad (7)$$

This enables us to write equations (6) as the single equation

$$\mathbf{A}\mathbf{N} = 0. \quad (6a)$$

The additional vector and matrix quantities in equations (6) and (6a) are defined in general as

Stoichiometric coefficient vector, ν : any non-zero vector of N real numbers satisfying the equation $\mathbf{A}\nu = 0$; and

Complete stoichiometric coefficient matrix, \mathbf{N} : a matrix whose R columns are stoichiometric vectors with the additional specification that $R = N - \text{Rank}(\mathbf{A})$, equation (5).

An alternative way of writing equations (6) explicitly involving the columns of \mathbf{A} is

$$\sum_{i=1}^N \mathbf{a}_i \nu_{ij} = 0; j = 1, 2, \dots, R, \quad (6b)$$

where ν_{ij} is the stoichiometric coefficient of the i th species in equation j . A set of chemical equations results from equations (6b) when we replace the formula vectors \mathbf{a}_i by their species names, A_i :

$$\sum_{i=1}^N A_i \nu_{ij} = 0; j = 1, 2, \dots, R. \quad (8)$$

Equations (K') and (L') above together are an illustrative set of equations (8) for the system made up of reacting species CH_4 , S_2 , CS_2 , H_2S and H_2 . Thus such equations are a chemical shorthand way of writing the vector equations (6b). By definition a

Complete set of stoichiometric equations is the set of equations (8), where the ν_{ij} form a complete stoichiometric coefficient matrix \mathbf{N} , as defined above.

In passing, we point out that the parameters ξ_j in equations (4), and the corresponding ξ 's in the examples above, are the "extent of reaction" parameters introduced by De Donder [34].

If we define

$$C = \text{Rank}(\mathbf{A}), \quad (9)$$

the significance of C is as follows: we can solve equations (1) for C n_i 's given R n_i 's, provided the formula vectors of those C n_i 's are linearly independent. This is equivalent to partitioning the species involved into two groups, components (numbering C) and non-components (numbering R), as discussed above, where the components may be regarded as chemical "building blocks" for forming the non-components in chemical equations, one equation being required for each non-component. This leads to the definition of a

Component: one of a set of C species of the chemical system, the number of which is the least number required to make up any compositional state of the system; the formula vectors of these species must have the property that $\text{Rank}(\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_C) = C$, where $C = \text{Rank}(\mathbf{A})$.

GENERAL PROCEDURE

The procedure simultaneously determines rank (\mathbf{A}) and a complete set of chemical equations. A Fortran computer program implementing it is available from the authors, and we describe the "hand-calculation" procedure below.

The steps are as follows:

1. Write the formula-vector matrix, \mathbf{A} , for the given sys-

We wish to emphasize that the stoichiometric description of a chemical system can be obtained solely from a list of the species and elements involved. It does not require, initially, a set of chemical equations.

tem, with each column identified at the top by the chemical species represented.

2. Form a unit matrix as large as possible in the upper-left portion of A by elementary row operations, and column interchange if necessary; if columns are interchanged, the designation of the species (at the top) must be interchanged also. The final result is a matrix A^* .

3. At the end of these steps, the following are established:

- the rank of the matrix A , which is C , the number of components, is the same as the number of 1's on the principal diagonal of A^* ;
- a set of components is given by the C species above the columns of the unit matrix;
- the maximum number of linearly independent stoichiometric equations is given by $R = N - C$;
- the stoichiometric coefficients of a permissible set of these equations are obtained from the columns of the part of the matrix A^* to the right of the unit matrix; each column relates to the formation from the components of one mole of the species whose designation heads that column, and the entries in the column refer to the stoichiometric coefficients of the components in the order of the component columns in the unit matrix.

The following illustrations demonstrate the procedure, and also show how inert species and charged species are treated.

Illustration 1. For the system



determine F_s , C and R , and a permissible set of chemical equations. Note that N_2 is inert.

Solution: Following the steps outlined above, we have

$$1. \quad A = \begin{matrix} & (1) & (2) & (3) & (4) & (5) & (6) \\ \begin{pmatrix} 0 & 2 & 2 & 4 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 2 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{matrix}$$

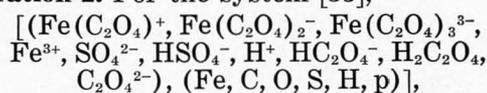
Here the numbers at the tops of the columns correspond to the species in the order given, and the rows are in the order of the elements given.

2. The matrix A can be put in the following form by means of elementary row operations and column interchanges:

$$A^* = \begin{matrix} & (3) & (1) & (2) & (6) & (4) & (5) \\ \begin{pmatrix} 1 & 0 & 0 & 0 & 4 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & -2 & -1 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \end{matrix}$$

3. (i) rank (A) = 4 = C ;
(ii) a set of components is H_2 , CO_2 , H_2O , and the inert N_2 ;
(iii) $R = N - \text{rank}(A) = 6 - 4 = 2 = F_s$
(iv) the set of two equations indicated by the entries in the last two columns is
 $4\text{H}_2 + 1\text{CO}_2 - 2\text{H}_2\text{O} = \text{CH}_4$,
and $1\text{H}_2 + 1\text{CO}_2 - 1\text{H}_2\text{O} = \text{CO}$,
or, as we would usually write them,
 $4\text{H}_2 + \text{CO}_2 = 2\text{H}_2\text{O} + \text{CH}_4$,
and $\text{H}_2 + \text{CO}_2 = \text{H}_2\text{O} + \text{CO}$.

Illustration 2. For the system [35],



determine F_s , C , and R , and a permissible set of chemical equations.

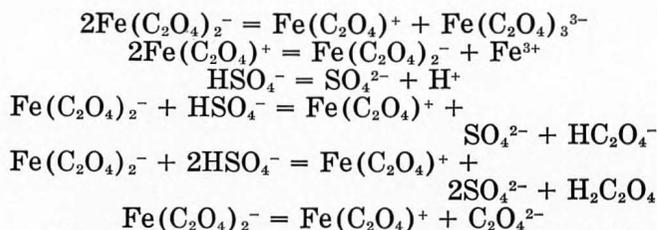
Solution: Following the steps outlined above, we have

$$1. \quad A = \begin{matrix} & (1) & (2) & (3) & (4) & (5) & (6) & (7) & (8) & (9) & (10) \\ \begin{pmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 4 & 6 & 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 \\ 4 & 8 & 12 & 0 & 4 & 4 & 0 & 4 & 4 & 4 & 4 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 2 & 0 & 0 \\ 1 & -1 & -3 & 3 & -2 & -1 & 1 & -1 & 0 & -2 & 0 \end{pmatrix} \end{matrix}$$

2. The matrix A can be put in the following form:

$$A^* = \begin{matrix} & (1) & (2) & (5) & (6) & (3) & (4) & (7) & (8) & (9) & (10) \\ \begin{pmatrix} 1 & 0 & 0 & 0 & -1 & 2 & 0 & -1 & -1 & -1 & -1 \\ 0 & 1 & 0 & 0 & 2 & -1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & -1 & -2 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{matrix}$$

3. (i) rank (A) = 4 = C ;
(ii) a set of components is $\text{Fe}(\text{C}_2\text{O}_4)^+(1)$, $\text{Fe}(\text{C}_2\text{O}_4)_2^-(2)$, $\text{SO}_4^{2-}(5)$ and $\text{HSO}_4^-(6)$;
(iii) $R = N - \text{rank}(A) = 10 - 4 = 6 = F_s$
(iv) the set of six equations indicated is



In conclusion, we wish to emphasize that the stoichiometric description of a chemical system can be obtained solely from a list of the species and elements involved. It does not require initially a set of chemical equations, no matter how generated. However, if a set of chemical equations is used initially, the set can similarly be tested to determine the maximum number of independent equations [3a]. We do not recommend this approach for a stoichiometric point of view, but rather recommend the approach, as described here, that begins with the list of species and generates a permissible set of equations. □

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ChE news

ROBERT PERRY DIES

Robert H. Perry, former professor of chemical engineering at the University of Rochester, died Thurs., Nov. 9, in Crawley (Sussex) England. He was 54 years old. Perry was a member of the University of Rochester faculty from 1964 to 1968, and served for a year as acting chairman of the ChE department and as associate dean of the College of Engineering and Applied Science from 1965 to 1968. Highly regarded as a teacher, researcher, administrator, and engineer, Perry was editor-in-chief of the fourth and fifth editions of the "Chemical Engineers' Handbook." During his career he served as chairman of the ChE department at the University of Oklahoma, program director for science faculties with the National Science Foundation, and research engineer for several corporations. In 1961 he assisted UNESCO in establishing a new technical university in Ankara, Turkey. A chemistry graduate of Dartmouth, Perry held B.S. and Ph.D. degrees in ChE from the University of Delaware and an M.S. in ChE from MIT.

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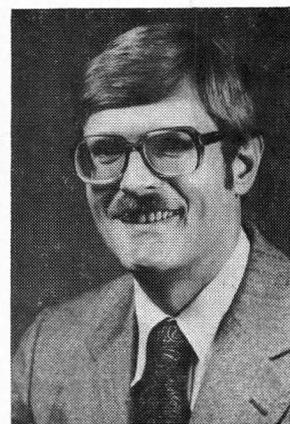
MODELS FOR TURBULENT TRANSPORT PROCESSES*

JAMES C. HILL
Iowa State University
Ames, Iowa 50011

STATISTICAL THEORIES OF turbulence have developed quite rapidly over the last twenty or thirty years but are, unfortunately, so abstract, unwieldy, and unreliable that chemical engineers seldom make any use of them. When one needs to design a mixing nozzle for a pipeline reactor or to estimate the ground level concentration of hydrocarbon emissions from a process unit, one is not inclined to read a discourse on the ergodic nature of d-dimensional turbulence. (For good reviews of statistical turbulence theory, intended for the semi-specialist, consult References 1-3.) Even the first of the modern statistical theories, the direct interaction approximation [4] or DIA, is so difficult and expensive to use that very few calculations have been made with it. Instead we use ideas only slightly more advanced than those proposed by St. Venant and Boussinesq over a century ago.

Single point closures, on the other hand, show more promise and do not require orders of magnitude more computing power than do laminar flow problems. Furthermore, they can be formulated to have some quantitative contact with the actual dynamical equations [5, 6]. Most of the advances in the technique of single point closures (or single point models) are being made by mechanical and aerospace engineers; very few ChEs seem to be involved in the activity. It is the purpose of this paper to introduce more of us (especially educators) to the subject and to suggest some areas of needed research. Many reviews of various aspects of the subject are available [7-15, for example], and so only a brief outline is presented here. For background any of the standard texts on turbulence should be consulted [16-18].

*This paper, submitted after much prodding from the Editor, is based on the 10-minute talk, "Problems With Current Models of Turbulent Transport," which was presented at the New York AIChE Meeting (1977) as part of a panel discussion on research needs in turbulent transport and mixing.



Jim Hill is Associate Professor of ChE at Iowa State, which he joined in 1971. He has a B.S. degree from Stanford University and a Ph.D. degree from the University of Washington, was a NASA post-doc at Goddard Space Flight Center, has worked for Shell Development Company, and spent last year at the National Center for Atmospheric Research in Boulder, Colorado. His research interests are fluid mechanics, turbulence, and air pollution control of aerosols. Most recently, between volleyball tournaments and handball matches, he has been involved with direct numerical simulation of the turbulent mixing of passive scalars, with and without chemical reaction.

TURBULENT TRANSPORT PROBLEMS

A MODEL OF TURBULENT transport is simply a mathematical representation of the process, and there are many kinds available. Certain models are more appropriate than others, depending on the type of problem and the property being transported. For example, many dispersion (i.e., making diffuse) and mixing (i.e., making uniform) processes that occur in wall turbulence, free shear layers, and wakes appear to involve gradient transport, and so this feature should be preserved in those models.

The information desired from the problem also affects choice—or perhaps availability—of a model. For example, if knowledge of rate and extent of transport is required, then mean single point information may suffice; but if spatial structure of the transported property is needed, at least two-point closures are needed.

Other considerations that influence the avail-

ability or appropriateness of certain kinds of models include the presence of interfaces (i.e., single phase or multiphase system?), complicated geometry, transient behavior, and whether or not chemical reactions, variable fluid properties, and non-Newtonian flow behavior can be treated. The dynamical models described below are limited to single phase flows.

TYPES OF MODELS

AN ARBITRARY CLASSIFICATION of the available types of turbulent transport models appears in Table 1. By far the most common models are the empirical type that involve experimentally determined parameters such as j-factors, heat transfer coefficients, and the like. These models may incorporate sound physical ideas, such as the weak Reynolds number dependence of large eddy processes.

Mechanistic models, the second category, modify the true physics by assuming that certain mathematically more tractable mechanisms dominate the transport process. Examples include mixing length models (which may also be imbedded in dynamical models), surface renewal theory, coalescence-dispersion models, Reynolds and Martinelli analogies, etc.

Dynamical models, the third category, are based to a considerable extent on the true dynamical equations describing the process, e.g., the Navier-Stokes equations or the convective mass transport equation. There is danger that the approximations invoked to permit solution may distort the physics more than direct use of a mechanistic analog, but dynamical models have the promise of being formulated for very general applications. The models may be semi-empirical, i.e.,

TABLE 1
Types of Models of Turbulent Transport

- | | |
|------------------------|--|
| 1. Empirical Models | Transport coefficients |
| 2. Mechanistic Analogs | "Exact" solution of plausible analog |
| 3. Dynamical Models | "Approximate" solution of averaged equations of change |
| 4. Other | |

TABLE 2
Desiderata for Turbulence Models
(A Disjoint Set of Needs)

1. Adequate representation of the physics
2. Ability to solve realistic problems
3. Ease of computation

contain phenomenological coefficients, or may be more or less rigorously derived using some statistical hypotheses.

Everything else is in the fourth category, including integral methods that require parameter estimation (by the techniques of either of the first two categories) and also large eddy simulations in which the large scale flow structure is solved numerically but with a 'sub-grid' model that accounts for the dynamics of the small scales [13].

The ideal model—if it were to exist—would satisfy the criteria listed in Table 2. Let us now briefly look at dynamical models to see how good they are in this regard.

DYNAMICAL MODELS

TABLE 3 DISPLAYS A sample of the available kinds of dynamical models, mostly for momentum transport, the preponderance of which are unsuited for practical application and are still subjects of research. The classifications should not be taken too seriously. The name 'single-point' refers to dynamical equations that apply to single spatial points, whereas 'two-point' theories involve correlations or spectra. The order of the model is the order of the equation in which the closure or modeling is made; for example, second order closures involve dynamical equations that are second order in the dynamical variables.

1. Single Point Models

To illustrate single point closures, consider the Reynolds equation obtained by averaging the Navier-Stokes equations:

$$\frac{D\bar{U}_i}{Dt} + \frac{\partial}{\partial x_j} (\overline{u_i u_j}) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \nabla^2 \bar{U}_i \quad (1)$$

$$\partial \bar{U}_i / \partial x_i = 0 \quad (2)$$

When one needs to design a mixing nozzle for a pipeline reactor or to estimate the ground level concentration of hydrocarbon emissions from a process unit, one is not inclined to read a discourse on the ergodic nature of d-dimension turbulence.

TABLE 3
Dynamical Models of Turbulent Transport

	SINGLE-POINT	TWO-POINT	THREE-POINT AND MORE
First Order	Eddy-coefficient (ν_T, D_T) Mixing length	Quasilinear (Deissler, Loeffler, etc.)	none
Second Order	One and Two-Equation Transport Models [e.g., k- ϵ models] Launder, Spalding, Kolmogorov, Lumley, Harlow, Saffman, Kovaszny, Wolfshtein, Jones & Launder, Harsha, etc.) Stress Equation Transport Models [e.g., k- ϵ - uv] (Rotta, Donaldson, Harlow, Hanjalić & Launder, Wolfshtein et al., Launder-Reece-Rodi, etc.)	Spectral Theory and Cascade Models (Kolmogorov, Heisenberg, Batchelor, Corrsin, Leith, etc.) [including Corrsin isotropic mixer] Statistical Theory (Kraichnan [DIA, LHDI, TFM], Orszag, Herring, etc.)	3-point Green's Functions (Weinstock)
Third and Higher Order	Higher Order Transport Models [$\overline{u\epsilon}$, etc.] (Chou, Davidov)	Higher Order Statistical Theory [including distribution functions]	Higher Order Statistical Theory [including functionals (Hopf, etc.)]

where

$$U_i = \overline{U}_i + u_i \quad \text{and} \quad \frac{D}{Dt} = \frac{\partial}{\partial t} + \overline{U}_i \frac{\partial}{\partial x_i}$$

Equation (1) may be closed at the first order with an eddy viscosity model,

$$\overline{u_i u_j} = -\nu_T \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) + \frac{2}{3} k \delta_{ij} \quad (3)$$

where k is the turbulent kinetic energy $k = \frac{1}{2} \overline{u_i u_i}$ and ν_T is the eddy viscosity, which may be represented as $l_{\text{eddy}} v_{\text{eddy}}$. Some forms for ν_T are

$$\nu_T = \begin{cases} l^2 |\partial \overline{U}_i / \partial x_j| & \text{(Prandtl 1925)} & (4a) \\ c_1 k^{1/2} l & \text{(Prandtl 1945)} & (4b) \\ c_2 k^2 / \epsilon & \text{(Kolmogorov 1942)} & (4c) \end{cases}$$

The stress equation models, for example, correctly predict negative eddy viscosity effects, secondary flow in noncircular ducts, and are accurate for thin shear flows.

where the turbulent dissipation rate, $\epsilon = \nu (\overline{\partial u_i / \partial x_j})^2$, may be evaluated as $\epsilon = c_3 k^{3/2} / l$, and where l is a prescribed turbulent length scale. This first order model, Eq. (1)-(3), is inadequate for complex flows.

Second order transport models introduce auxiliary dynamical equations for such quantities as k , l , and $\overline{u_i u_j}$. The prescription for one- and two-equation models is to a) express ν_T by Eq. (4b) or (4c), b) develop a transport equation for k or ϵ based on the Navier-Stokes equations, and c) prescribe l or develop a transport equation for $k^m l^n$. The best known example of the two equation model is that of Jones and Launder [19],

$$Dk/Dt = \nabla \cdot \left(\frac{\nu_T}{\sigma_k} \nabla k \right) - \overline{u_i u_j} \frac{\partial \overline{U}_i}{\partial x_j} - \epsilon \quad (5)$$

$$D\epsilon/Dt = \nabla \cdot \left(\frac{\nu_T}{\sigma_\epsilon} \nabla \epsilon \right) - c_4 \frac{\epsilon}{k} \overline{u_i u_j} \frac{\partial \overline{U}_i}{\partial x_j} - c_5 \frac{\epsilon^2}{k} \quad (6)$$

in which the σ 's (turbulent "Prandtl" numbers) and the c 's must be obtained from experiment, and

The name 'single-point' refers to dynamical equations that apply to single spatial points, whereas 'two point' theories involve correlations or spectra.

(4c) is used for ν_T .

Stress-equation models, such as the Launder-Reece-Rodi or LRR model [20], were introduced by Rotta in 1951 and are now considered superior to the two-equation models. (See also the recent promising work of Jeandel et al [21].) Instead of (33, a dynamical transport equation for $\overline{u_i u_j}$ is formulated using the Navier-Stokes equations, to obtain (symbolically)

$$\frac{D}{Dt} \overline{u_i u_j} = P_{ij} + D_{ij} - \frac{2}{3} \epsilon \delta_{ij} + \phi_{ij} \quad (7)$$

$\frac{D\epsilon}{Dt}$ = stress generation + diffusional transport plus dissipation plus pressure-strain redistribution.

In (7) the stress generation term P_{ij} (from mean gradients and body force) is treated exactly, "diffusional" transport D_{ij} (the divergence of triple products) is modeled by gradient diffusion, the dissipation term assumes isotropy of the small scales, and the pressure-strain redistribution term (which involves unmeasurable pressure-velocity correlations) is nothing but trouble. ϕ_{ij} varies from one modeler to the next; usually a form is used based on almost-isotropic turbulence, even for thin shear layers. In flows where stress generation and dissipation are not in good local balance, ϕ_{ij} causes problems. So does the present form of Eq. (6).

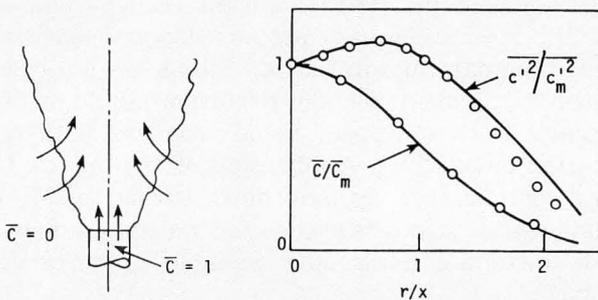


FIGURE 1. Sketch of typical predicted (solid lines) and measured (circles) mean concentration and concentration fluctuation intensity profiles for a round jet (after Spalding [10]). The subscript m denotes center-line value, r and x are radial and axial coordinates.

Similar developments have been made for scalar fields, i.e., heat and mass transfer [12]. The appropriate 'scalar flux' equations needed are

$$\frac{D\overline{C}}{Dt} + \frac{\partial}{\partial x_i} (\overline{u_i c}) = D\nabla^2 \overline{C} + \overline{R} \quad (8)$$

$$\frac{D}{Dt} \overline{u_i c} = \text{somewhat similar to (7)}. \quad (9)$$

As in (7), the pressure-concentration gradient correlation causes difficulty. Scalar transport mod-

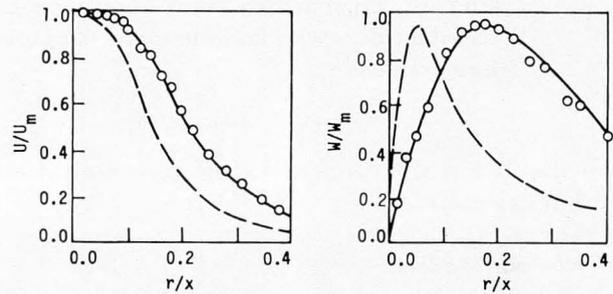


FIGURE 2. Sketch of axial (left) and circumferential (right) velocity profiles predicted by Reynolds stress closures [23] for swirling jet in stagnant surroundings at $x/D = 6$. The circles represent experimental data, the dashed lines are for the standard form of pressure-strain correlation ϕ_{1j} (LRR model), and solid lines have circumferential components of ϕ_{1j} reduced by 60%.

els have recently been generalized to higher order by Deardorff [22].

The single point models—especially the stress equation and concentration flux models—have had many successes. The stress equation models, for example, correctly predict negative eddy viscosity effects, secondary flow in noncircular ducts, and are accurate for thin shear layers. An illustration of successful application of a second order closure to the concentration distribution in a jet is shown in Fig. 1. On the other hand, weak shear (far wake), rapid decay (round jet), swirl flows, buoyancy effects, and recirculation lengths are poorly treated if one insists that the empirical constants (the c's and σ 's) be universal, i.e., be evaluated with other types of flows. In the swirl jet, for example, spreading rate and even the sign of the Reynolds stress are in error, leading to the poor agreement shown in Fig. 2. Computational requirements for all of these models are quite modest, in comparison with multipoint statistical

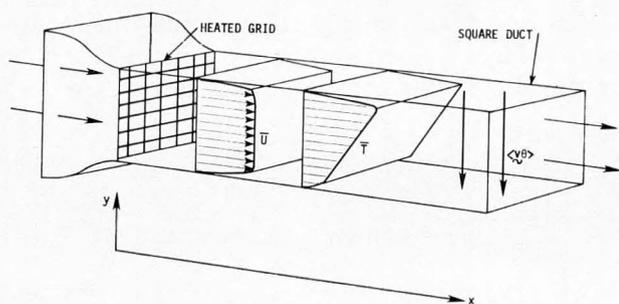


FIGURE 3. Wind tunnel with heated grid used by Wis-kind [24] to generate a nearly homogeneous turbulent flow with uniform mean temperature gradient.

theories, the main concern being core-limitation for 3-D calculations.

2. Two-Point Models

Two-point models, especially those based on statistical theories, are relatively undeveloped for engineering problems. The present author, for example, has applied the direct interaction approximation to heat transfer in a grid flow (Fig. 3); the results for variation of eddy diffusivity E_H

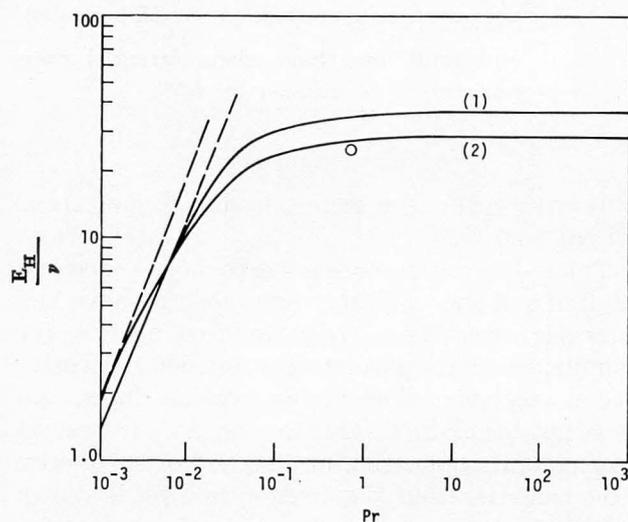


FIGURE 4. Estimates of Prandtl number dependence of thermal eddy diffusivity E_H based on unpublished direct interaction approximation (DIA) calculations by the author. Curve (1) assumes a Gaussian shape of the longitudinal two-point two-time velocity correlation function; curve (2) assumes exponential shape. The dashed lines are theoretical low-Pr asymptotes and the one data point (air) was taken by Wiskind.

with Prandtl number (Fig. 4) for this simple problem would cost tens of \$1000 today in computer time alone (the programming itself is quite formidable), so it is not surprising that statistical theory is not used much.

WHAT IS NEEDED

THE SINGLE POINT transport models described above satisfy the criteria in Table 2 better than most other models for single phase flows. Some areas of research that would improve their usefulness are listed in Table 4. Some areas are virtually untouched because ChEs have not yet been involved much.

Modeling the essentially unmeasurable pressure correlations for ϕ_{ij} in Eq. (7) is a major problem, but large eddy simulations may be helpful to examine the term. Chemical reactions have been largely neglected [11]; current closures for non-linear chemistry are inadequate, especially for

TABLE 4
Suggested Research Areas

Pressure correlations	Time-dependent problems
Chemical reactions	Multiphase flow
Two-point models	Non-Newtonian fluids
Eddy structure	Variable-property effects
Error propagation	Complicated, realistic flows

complex reactions, and the newer models have not been tested against liquid phase (high Schmidt number) experiments. Two-point models, necessary for description of spatial structure, are too complicated for shear flows; furthermore, many basic problems in spectral theory are still unresolved, including diffusive subranges, small scale dynamics, etc. New ideas about eddy structure, especially near the wall and in free shear layers, have not been incorporated in the transport models. The problem of error propagation and sensitivity to boundary and initial conditions has not been addressed. Time-dependent problems should be examined, as there appear to be problems with relaxation effects [23]. Application of the models to very complicated, realistic flows is sparse. More fundamental theory is needed for multiphase flows, non-Newtonian fluids, and variable property effects.

Although the above list is long, it is formulated in response to the fine successes that single point models have had. If we can manage to get these models to work accurately and reliably for us, perhaps we will have more time to read about d-dimensional turbulence. □

ACKNOWLEDGMENTS

Preparation for the New York panel discussion—and hence this paper—was made when the author was a Senior Postdoctoral Fellow in the Advanced Study Program at the National Center for Atmospheric Research, while on Faculty Improvement Leave from Iowa State University. The author gratefully acknowledges these two programs and the Engineering Research Institute at Iowa State. NCAR is supported by the National Science Foundation.

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ChE book reviews

THE INTERPRETATION AND USE OF RATE DATA: THE RATE CONCEPT

By Stuart W. Churchill
McGraw-Hill, New York, 1974.
Reviewed by Robert L. Kabel,
Pennsylvania State University

"The Interpretation and Use of Rate Data" does not fit in well with conventional chemical engineering curricula. However, the book is so unique and important that a way must be found to convey its message to students and practicing engineers. By the way, is the distinction between a *rate of change* and a *process rate* fuzzy in your mind?

Churchill has treated the rate processes involved in heat transfer, momentum transfer, component (mass) transfer, bulk transfer, and chemical reactions according to a rather general "Rate Concept." In all of these areas the treatment is at the level of sophomore and junior chemical engineering courses. Attention is focused on principles and procedures rather than on process complications by considering primarily one-dimensional processes which can be described in terms of algebraic or separable differential equations. About one-third of the book is devoted to chemical reactions, but all topics are intermingled in such a way that the generalizations and methods are emphasized instead of the specific applications. This reviewer used all of the material on chemical reactions in a review portion of an advanced kinetics course and he read the remaining material concurrently.

Following the introductory material, the early emphasis is on real data and data handling. There is then a shift to data correlation and finally to process analysis. This order of presentation is the reverse of that almost always encountered by

Continued on page 44

RENEWED EMPHASIS ON TECHNICAL COMMUNICATION AT TEXAS TECH

RICHARD WM. TOCK and
CHARLES (BILL) BREWER
*Texas Tech University
Lubbock, Texas 79409*

ASK A PRACTICING chemical engineer the following question:

“Do you consider writing ability to be essential to the performance of your job?”

Ninety-five percent of those responding will probably answer in the affirmative. At least that was the response obtained from 135 graduates of ChE from Texas Tech University who were polled about the importance of technical communication. This appears to be a typical attitude representative of all engineering professions. For example, articles on how to write better reports appear routinely in professional journals [1, 2, 3]. And, if the information is to be transferred to the public domain, professional societies provide ample information for the author on procedures for presenting papers at professional society meetings or in professional journals. Admittedly these instructions deal more with “form” rather than “style”, but the desire for clarity is still universal.

It is somewhat surprising, therefore, to learn that there is a growing concern among educators about the inability of students (and ultimately engineers) to communicate [4, 5, 6, 7, 8]. At the university level there has, of course, been a reduction of formal instruction on communication skills in engineering degree programs over the last two decades. Surveys by the AIChE reveal that the average semester hours of credit required in communications courses in ChE curricula has dropped 50 percent, from eight hours in 1957 to four hours in 1976 [9]. Whether or not this de-emphasis has contributed to the overall decline in the communications skills of engineering graduates is still open to conjecture. However, because of an apparent low level of performance in rhetoric by senior

... the Technical and Professional
Writing Program of the English Department
was asked to prepare and administer a course
in technical writing.

students, the ChE Department at Texas Tech decided to re-emphasize technical communication skills.

At the beginning of the 1974-75 academic year the department initiated a program which it hoped would enhance the technical-writing skills of graduates. To accomplish this, the Technical and Professional Writing Program of the English Department was asked to prepare and administer a course in technical writing. This instruction was to be supportive of the normal report writing required in the senior level unit-operations course sequence. The final format which evolved required each student to receive one hour of instruction per week on the basics of technical communication. The students were then asked to write their unit-operations reports based on a variety of criteria. For example, they were asked to submit their reports in either (1) letter form, (2) as a memorandum or (3) as a fully documented formal report. In addition, they were asked to write for a variety of readers such as (1) a nontechnical administrator, (2) nonscientific personnel, or (3) a fellow engineer. A total of eight to ten reports were prepared by each student throughout the two-semester course sequence. In order to evaluate a student's performance, a member of the engineering faculty graded the reports on their technical content while report-design elements (language, style, and format) were evaluated by the faculty representative from the English Department. The final course grade, therefore, became an evaluation of the student's ability to master the technical aspects of the unit-operations course as well as his effectiveness in communicating this technical information.

COURSE DESCRIPTION

THE TECHNICAL CONTENT of the unit-operations course did not change appreciably following the adoption of the new program. In general it followed a traditional format in which the students were divided into working teams of three to four members. The groups were then assigned four experiments to be carried out during the semester. These included the standard heat and mass transfer studies, those experiments

which gave a combination of heat and mass transfer, a kinetics experiment, and a system to elucidate mixing operations. A list of the experiments performed is shown in Table 1.

In general, the difficulty of the experiments varied from rather simple repetitive measurements to the development of complicated abstract concepts. Hence the students were subjected to varying degrees of difficulty in the type of technical information they were asked to communicate.

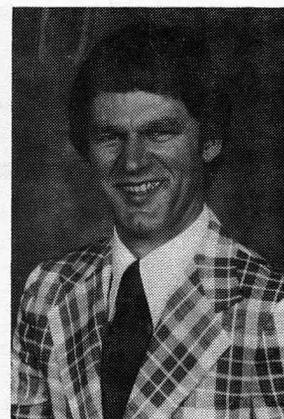
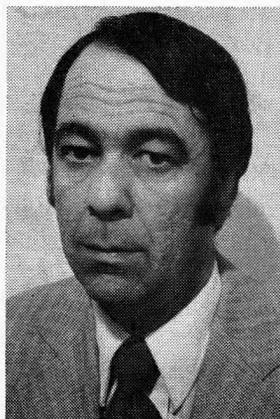
Communications content of the course is based on the coursework-design used in Technical and Professional Writing Program courses. Texas Tech offers a major in technical writing and editing based on many new concepts in writer training developed and tested over the past five years. In the unit operations laboratory the central concept used has been an "engineered approach" to writing.

In the "engineered approach", writing solely to convey information is not stressed. Instead, the objectives to be achieved (design criteria), audience characteristics (materials), and design tech-

TABLE 1
Unit Operations Laboratory Experiments

1. Fluid flow
 - a. Friction factor for fluid flow in pipes
 - b. Newtonian and non-Newtonian fluid behavior
 - c. Venturi and orifice meter measurements
2. Heat Transfer
 - a. Free and forced convection systems
 - b. Drop and film condensation
 - c. Double pipe heat exchangers performance
3. Mass transfer
 - a. Liquid-liquid extraction
 - b. Filtration of aqueous slurries.
4. Combinations of heat and mass transfer
 - a. Distillation
 - b. Evaporation
 - c. Humidification
 - d. Drying
5. Chemical kinetics
6. Unsteady-state operations
 - a. Mixing coupled with titration
 - b. Stirred-tank cooling

niques (methods), are strongly emphasized. An algorithmic method for report design is taught in order to convey the step-by-step procedure required for predictably successful writeups. Sentence structure presentations are adopted from recent results in linguistics. Enabling students to describe relationships between sentences ("good" and "bad" ones, ones linked together by para-



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Richard Wm. Tock is an Associate Professor in ChE at Texas Tech University. He received his B.S., M.S., and Ph.D. degrees in ChE at the U. of Iowa where he also taught for several years following graduation. His industrial experience includes serving as a Research Engineer in the Central Research Division of Monsanto Company and various consulting services. (R)

graphing, ones having the desired effects on readers, etc.) is a primary objective. Report format for memorandum, letter, and formal reports is adopted from American Chemical Society publication specifications.

Grading reports is like real-world evaluation of engineering work based on the twin criteria of effectiveness and efficiency in achievement of communications objectives. Misspelled words, for examples, are not frowned on for reasons of social unacceptability or instructor disapproval; they are disparaged because they are not effective or efficient in a report's achieving objectives among persons who recognize them as misspelled words.

Classwork and grading procedures are supplemented by conferences with students. The conferences are designed to provide tutorial teaching and provide additional rapport between ChE students and technical-writing teachers.

Three types of reports are required in the course in order to simulate the complete spectrum of writing required of professional engineers. Formal reports correspond to well documented communications for wide distribution throughout a company, an industry, or a profession. Memorandum (short-form) reports correspond to col-

Three types of reports are required in the course in order to simulate the complete spectrum of writing required of professional engineers.

league and management oriented communications within an organization. Letter reports correspond to contract related communications between two organizations. Differences and similarities among audiences of the three reports—as well as format and language differences and similarities—are stressed as key materials in report design.

PROGRAM EVALUATION

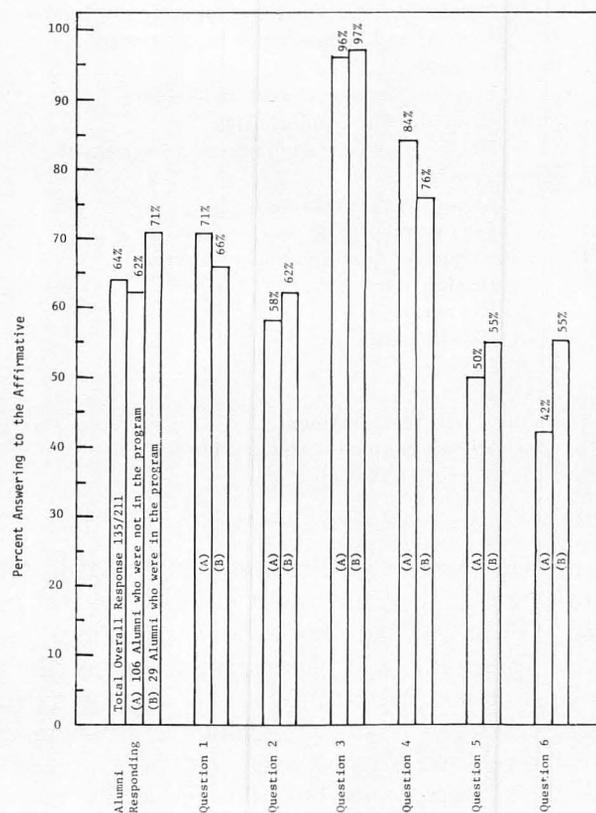
IN GENERAL THE FIRST few semesters of the program were qualitatively evaluated by the professors involved in the instruction. Simple improvement in an individual student's performance seemed to suggest that the added emphasis given to technical communication was indeed accomplishing its goal. This achievement was not without conflict, however. Initially some students were unhappy with the added time spent in the technical-writing class and the additional assignments. Many students also expressed strong feeling about having their papers graded by two different professors and on two different bases: for technical content and for communication effectiveness and efficiency. Nor did all the voiced dissent come from the students. There was some disagreement among the faculty during the initial stages of the program concerning the proper format and style to be followed in the reports. Fortunately, time and compromise have brought solutions to most of these early conflicts. Now a manual of instruction is being developed to help formally establish the program. In addition, several other engineering departments have begun similar technical-communications instruction within their own courses.

Even though the new program appeared to be successful, it was deemed desirable to have some additional evidence of its success. Moreover, it was felt that some input from graduates of the program would be helpful in developing an even more effective program in communication skills. Consequently, a short questionnaire was developed and mailed to department graduates from the preceding eight years. These alumni included graduates from the last two years who had had the benefit of the new instructional program, as well as those from earlier years who had not ex-

perienced any formalized instruction outside of that supplied by the ChE faculty of the department. The following six questions to be answered "yes" or "no" were asked of each person in this group.

1. Did you receive all your undergraduate education at Texas Tech?
2. Do you feel the technical writing instruction you received at Texas Tech was adequate to meet the responsibilities of your job?
3. Do you consider writing ability to be essential to the performance of your job?
4. Do you feel a course in technical communication should be required for all B.S. engineering graduates?
5. Has your company ever offered to provide instruction for improving communication skills of its engineering employees?
6. If Texas Tech offered an off-campus course in communication skills at or near your plant location, would you attend?

The results of the questionnaire are summarized in the following graph. Of the 211 questionnaires mailed, 135, or 64 percent, were returned. For comparative purposes the responses were separated into two classifications: (a) those alumni who had only departmental emphasis given to their technical writing skills while attending Texas Tech and (b) those alumni who graduated



during the last two years and received the new instructional program developed by the English Department. The latter group composed 19 percent of the total responding population.

The response to Question 1 indicates that students at Texas Tech are following a national trend by obtaining some of their education at local or area schools before getting their final degree at a

at their convenience. On the surface it might appear as though the responses to Question 6 are not compatible with those of Question 2. One interpretation is that the increased emphasis on technical communication by the program has tended to make more students aware of their deficiencies. Hence they would aspire to do more work in this area to improve their abilities. There is also a certain de-

The groups were then assigned four experiments to be carried out during the semester. These included the standard heat and mass transfer studies, those experiments which gave a combination of heat and mass transfer, a kinetics experiment and a system to elucidate mixing operations.

state institution such as Texas Tech. This pattern of switching schools means that the final degree-granting institution has an added responsibility to their graduates. The students must be exposed to those basic fundamentals which will enable them to succeed. In the case of communication skill, competency is all too often inferred from transcripts and is rarely tested. Thus graduates may be ill prepared to meet their job requirements with respect to communication unless the university takes specific steps to prepare them.

Question 2 responses appear to support the general assumption that the program has had a positive impact. Thus, 62 percent of the people who had the new course felt it was adequate. However, a nearly equal 58 percent of those who didn't have the benefit of the new program felt that they still had received sufficient instruction. Question 4 might also be taken as proof of the program's success. In this case 76 percent of those in the course felt that a general program for all B.S. candidates was desirable while 84 percent of those not in the program felt it was. This implied that those having the new instructional program found it to be sufficient.

The answers to Question 3 indicate that the overwhelming majority of graduates feel their writing ability is essential to job performance. Apparently their companies do also, since for both populations (a and b) more than 50 percent of the responses to Question 5 indicated that they had been offered some form of additional instruction in writing. The 135 respondents worked for a total of 58 companies, 26 of which offered the additional instruction.

Finally, Question 6 seems to indicate that at least 40 percent of all the graduates are still willing to take more instruction if it were offered

gree of maturation which must be assigned to the earlier graduates of the population.

PROGRAM RESPONSE

ALTHOUGH THE GENERAL response of the questionnaire was judged to be supportive of the new program, some unsolicited written responses were even more enlightening. These are included in the Appendix in an abridged form. In addition to these longer comments there were several penciled replies. In general these were in reference to the necessity of good communication skills, and almost exclusively of the short letter form. Longer formal reports seemed to be within the purview of graduate degree holders and those in research groups. There were also comments encouraging the development of communication skills for transfer of technical information to the nontechnical person.

Finally, response from the technical writing faculty also seems to strongly support the program. Their observations include the following points.

- The senior unit-operations laboratory students, because of their level of maturity and their background in rigorous studies, grasp the material more rapidly and thoroughly than younger, less experienced students.
- The students are more highly motivated to learn writing procedures and techniques within the "applicative-oriented" context of unit-operations laboratory than are students in "stand-alone" technical writing courses.
- The "engineered approach" to writing used in the program dispels doubts and poor attitudes toward writing that may have resulted from less rigorous writing coursework undertaken during freshman college years or in public-school classroom.

In summary, responses to the questionnaire and responses of instructors indicate that the new emphasis on technical communication appears to

be accomplishing its intended goal. In addition, it has provided some valuable insights into some new directions the program might go in order to be more meaningful for the new engineer on the job. □

APPENDIX

Abridged Responses to the Questionnaire

"Tech writing at work is far different and less involved than those unit ops reports. I've written letters to spend \$15 million since I've been at work and have never written more than two pages per project."

"Tech writing: no need to emphasize technical aspects . . . concentrate on freshman English, basic grammar and sentence structure."

"For your information I now supervise the efforts of some twenty Chemical, Civil, Mechanical and Petroleum Engineers in our area office. I have found that the majority of the engineers on my staff, particularly those having just graduated from college, are weak in communication skills. I have also found that only about 50% of an engineer's total efforts are spent in technical analysis, the remaining 50% of an engineer's time is normally spent in "sales" of his ideas to his supervisors. As a result I feel that communication skills are of vital importance in the producing industry."

"I feel a course in written communication is justified, however I differ with the title "Technical Communication." Since most reports (or letters) are written to management, or with the intent of informing management, too much emphasis on the technical points can tend to confuse. I received most of my writing "training" while getting my MBA (whether popular or not). During this time I was forced to word both written and oral communications in terms nontechnical personnel could understand and relate to. In my opinion, writing could more easily and effectively be given by a department not so closely related to the detailed technical aspects."

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BOOK REVIEW: Rate Data Continued from page 39

students in their courses. In contrast to the usual classroom experience Churchill exposes students to lousy data, teaches data handling techniques, encourages critical evaluation and skepticism, and makes error analysis a reality. It becomes clear why rates of change are associated with derivatives and process rates are not. Adoption of his approach might even help to eliminate the widespread notion that the rate of a chemical reaction is equal to $(-dC/dt)$!

The book is liberally studded with quotations such as, "No generalization is wholly true, not even this one." My favorite came in Chapter 12 after an immoderate series of 24 batch system integrations (including 11 different ones in kinetics): "'One more such victory and I am lost.' Pyrrhus." The quotations were almost universally unpopular with the students, probably because they interfere with the most rapid search for the key to a homework problem solution. However a mature reader will find meaning (and frequently amusement) in nearly every one.

At the end of the course five students said they liked the book, three said they did not, and nine expressed no opinion. Two years later the same seventeen students were surveyed. There were eight respondents, all of whom thought the book was important or potentially valuable. Seven of them still had their copies, and three had used them on their jobs. Virtually all users will be inconvenienced by the absence of a nomenclature section. The units might be described as "early American traditional." Churchill could do all of us a favor, (and better demonstrate the coherence of the rate concept in diverse applications) if he would produce an SI edition.

It is easy to recommend the book to currently practicing individuals for self study. It is even pleasant bedside reading. For the most part the subject matter is familiar, but it appears in a new and interesting context which should increase understanding considerably. Unfortunately the implementation of routine use of this book in conventional undergraduate curricula is awkward at best. It could serve well as a text for a senior elective course. A colleague suggested using it in a seminar to introduce new graduate students to data handling and analysis in the determination of rates from experimental measurements. Ultimately, this review urges you to use your imagination to get its vital message through to chemical engineering students. □



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A 15-MONTH MS CHEMICAL ENGINEERING DEGREE PROGRAM FOR BS CHEMISTS

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FOR A NUMBER OF YEARS students graduating with a bachelor's degree in chemistry have found themselves facing rather poor employment prospects. Often students who desire a career in applied chemistry enter chemistry programs in four-year colleges and smaller state universities where no ChE curriculum is offered in order to be close to home or, perhaps, the tuition is lower. Traditional chemistry curricula cannot satisfy their needs. In order to achieve their real desires many of these students should be in a ChE program. Some ChE departments are developing special programs to offer a form of graduate ChE education to chemistry graduates [1, 2].

A few years ago the ChE Department at Brigham Young University (BYU) became aware of this dilemma faced by chemists as increasing numbers of applications for admission to graduate ChE programs were received from dissatisfied BS chemists. Under normal circumstances such applicants could not be admitted directly to our graduate ChE program because they lacked appropriate undergraduate ChE background training. This meant that for a BS chemist to obtain a MS degree in ChE, two academic years were required plus a summer for research and thesis writing. The first academic year was devoted to elementary undergraduate subjects. This is essentially the approach taken by Texas Tech [2], and is what Cussler [1] refers to as a remedial program. The prospect of two full additional years of school frequently served as a deterrent and few students undertook such a program.

A NEW APPROACH

WE DECIDED TO DEVISE a program which would shorten the time required for a BS chemist to obtain a MS degree in ChE without

sacrificing quality or soundness of training. We saw such a program both as an opportunity for chemistry graduates to gain a masters degree in ChE and as a service to many surrounding-area four-year college chemistry departments by providing a way for their industrially-oriented students to gain the further training they needed and desired. We also recognized it as a potential source of good first year graduate students to supplement the regular class of new ChE graduate students.

In order to maintain quality and a fundamental basis for such a program the chemist must be taught fluid mechanics, heat and mass transfer,

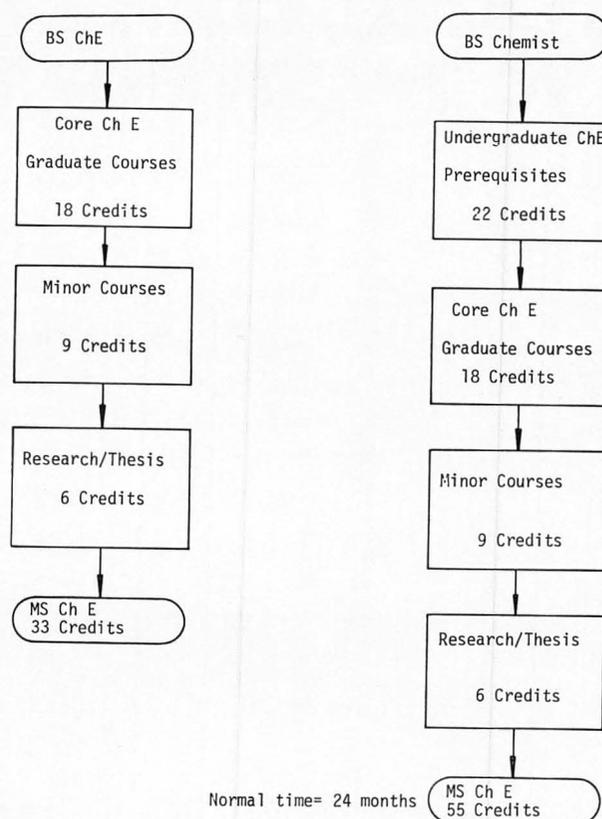
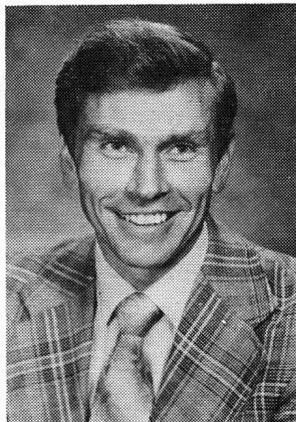


FIGURE 1. Flow chart for traditional MS degree program starting from BS degrees in Chemical Engineering and Chemistry (Remedial Track).



Richard W. Hanks is a professor in and Chairman of the Chemical Engineering Department at Brigham Young University where he has been a faculty member since 1963. He is author of numerous papers in transitional and turbulent fluid mechanics and solution phase equilibrium thermodynamics. Professor Hanks received his B.E. degree from Yale University in 1957, and his Ph.D. from the University of Utah in 1960. He has served as graduate coordinator of the Chemical Engineering Department at BYU for a number of years, was the initiator of this program, and handles all the recruiting activities. (L)

John Oscarson graduated from BYU in 1968 then did graduate work at the University of Michigan 1971-74 after serving in the military. His interests are transport phenomena and separation. He has taught the summer course the three years it has been offered. (R)

and separations technology, as well as kinetics, plant design and process synthesis and control. This training must be at the same level that is normally given regular ChE undergraduates who enter the graduate courses so that the chemists can successfully compete with ChE's.

The traditional MS degree course outline for a BS ChE and a BS chemist following the remedial track are illustrated in flow chart form in Figure 1. Clearly the problem for the chemist lies in the 22 semester hours of remedial undergraduate ChE prerequisites. These consist of: 1) a three-semester, 9-credit-hour series in unit operations (fluid mechanics, heat and mass transfer, and separations technology) spanning the junior year and part of the senior year of the undergraduate curriculum; 2) a two-semester, 4-credit-hour unit operations laboratory taught in the senior year; and 3) a three-credit-hour course in kinetics and reactor design and a six-credit-hour series of concurrent two credit-hour courses in plant design, process synthesis, and process control taught in the senior year.

In February 1976, the university granted the ChE department permission to undertake a new program which allows properly prepared BS chemists to obtain a MS degree in ChE in the normal 12

months plus one summer, or 15 months. The way this is accomplished is illustrated in flow chart form in Figure 2.

The key to shortening the time frame for the BS chemists lies in two modifications of the traditional program: (1) a special preparatory unit operations class, and (2) the minor. We recognized that chemists in their BS program take additional advanced level courses in chemistry, and sometimes physics and mathematics, beyond the usual physical chemistry requirement at which undergraduate ChE's normally stop. Most graduate students in ChE take their 9-credit-hour minor requirement in a "supporting field" arrangement. In this situation the minor courses may be drawn either from a single department or from a number of departments, and may range from upper division undergraduate to graduate courses in the supporting departments depending upon the student's preparation and degree of specialization.

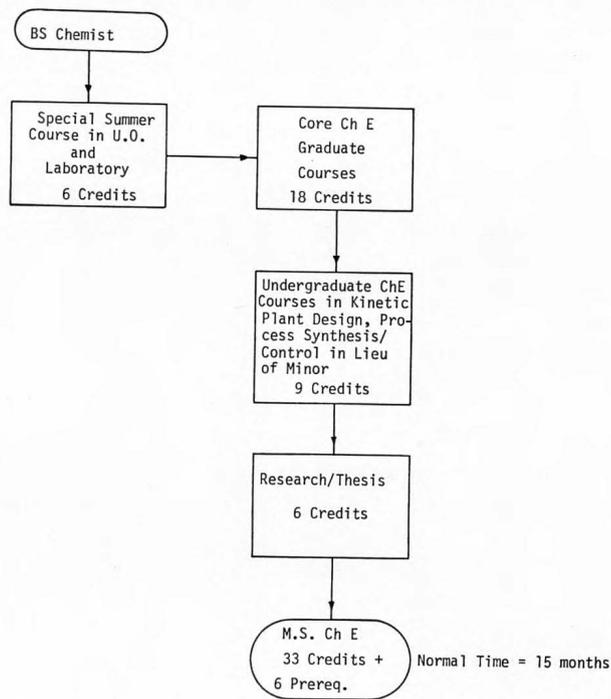


FIGURE 2. Flow chart for special MS degree program for well-prepared chemists.

We decided to devise a program which would shorten the time required for a BS chemist to obtain a MS degree in chemical engineering without sacrificing quality or soundness of training.

In developing this program we had to face the problem of what to teach a chemist to bring him "up to speed" in a short period of time. . . .

Thus, the advanced level chemistry and other technical courses usually taken by a senior chemist are generally equivalent to the supporting field minor frequently taken by a graduate ChE.

We decided to replace the usual 9-credit-hour minor requirement with 9 credit-hours of senior-level ChE courses formerly required as prerequisites (see Figure 1). Specifically, the courses chosen for this purpose were undergraduate kinetics, plant design, process synthesis, and process control (the latter two being open to both undergraduates and graduates).

This left only the unit operations and laboratory sequences to be dealt with. To cover this material we introduced a special 8-week, 6 credit-hour course taught from June through August which all entering BS chemists must take as a prerequisite to their graduate program. This special high-intensity course, which is described in more detail below, gives chemists the conventional unit operations course and laboratory all in one massive dose. This course is considered a remedial undergraduate preparation which must be passed before a chemist actually enters the M.S. program.

SPECIAL SUMMER CLASS

ENTRY TO THE NEW MS program must be through the special summer class. Chemists must also be properly prepared by having had a 3 credit-hour course in ordinary differential equations and a beginning course in FORTRAN programming as undergraduate students. If a chemistry student has not had these prerequisites, he or she must take them as remedial provisional re-

TABLE 1
MS Course Outline for BS ChE Student

COURSE NO.*	CREDITS		SP/SU
	FALL	WINTER	
672, 673, 676	3	3	3
675, 681	3	3	
677	1		
691R	1	1	
699R	1	2	3
Minor Electives	3	3	3
	12	12	9

*See Table 4 for explanation of course numbers

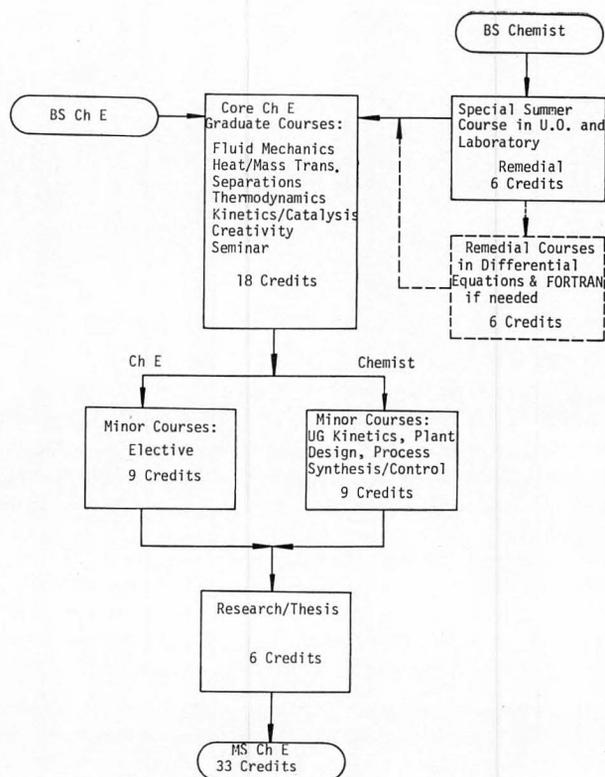


FIGURE 3. MS ChE degree program compatible with either a BS ChE or BS Chemistry degree. Normal time is 12 months for BS ChE student, 15 months for BS Chemist (may take 19 months if not prepared in math and computer programming).

quirements in addition to the usual graduate load. This usually necessitates an additional semester of work.

With the introduction of the special summer course and some slight modifications in the way in which some of the core graduate courses are taught and sequenced to better accommodate both types of entering students, we have finally devised the MS program outlined in Figure 3. This flow chart shows that the program is compatible with either a BS ChE or BS Chemistry degree as a starting point. Table 1 shows the typical course outline followed by the BS ChE student. Table 2 shows the corresponding course distribution taken by the properly prepared BS chemist. Table 3 shows a typical course outline for a BS chemist who requires remedial mathematics and computer work. Table 4 gives a brief description of each of the courses listed by number in the previous tables.

Some concern has been expressed [1, 4] that students graduating from programs which at-

tempt [1, 2] to retrain chemists may not really be ChE's. We believe that we have successfully coped with and overcome this objection in our program. A chemist who successfully completes our program will graduate having had precisely the same *graduate* ChE course work and thesis experience obtained by any undergraduate ChE who completes the regular MS degree program. The chemist will also have had the complete senior year ChE curriculum as well as the junior year unit operations and about half of the senior year unit operations lab courses. He will have had equal physics, mathematics, and general education training and superior chemistry training. The place where a difference occurs is that the chemist will not have had the usual undergraduate courses in electrical circuits and engineering mechanics. To this extent they are slightly less broadly exposed to engineering than the usual ChE undergraduate. We do not perceive this as being a critical deficiency. We believe that chemists who graduate from our program are adequately trained in ChE

TABLE 2
MS Course Outline for
Properly Prepared BS Chemistry Student

COURSE NO.*	CREDITS			
	SU	FALL	WINTER	SP/SU
693R	6			
672, 673, 676		3	3	3
478, 681		3	3	
677		1		
675		3		
691R		1	1	
464, 550, 551			6	
699R		1		5
	<u>6</u>	<u>12</u>	<u>13</u>	<u>8</u>

*See Table 4 for explanation of course numbers.

and can be viewed essentially as MS ChEs with a strong minor in Chemistry.

RECRUITING AND FINANCING

AN ESSENTIAL ELEMENT for the success of a program such as ours is the recruiting effort. In order to generate a reasonable size class, we initiated recruiting activities at all four-year colleges in the state of Utah and a few in selected neighboring states. Personal visits are made to chemistry departments where junior and senior undergraduate chemists are interviewed and the program is presented and explained. In order to present the program effectively, we prepared a slide presentation which describes career oppor-

TABLE 3
MS Course Outline for
BS Chemist Requiring Remedial Math/Computer Work

COURSE No.*	WIN-				
	SU	FALL-1	TER	SP/SU	FALL-2
693R	6				
675		3			
673, 676, 672			3	3	3
478, 681		3	3		
677					1
691R		1	1		1
464, 550, 551			6		
699R				3	3
Math 321		3			
CS 131		3			
	<u>6</u>	<u>13</u>	<u>13</u>	<u>6</u>	<u>8</u>

*See Table 4 for explanation of course numbers.

tunities in the chemical industry. The presentation outlines the differing roles of the chemist and the ChE, presents current job offer statistics and starting salary data for both, and outlines the BYU special program. This lecture is presented to both junior and senior chemistry majors, usually in a physical chemistry class. The usual response of chemistry department chairmen, especially in smaller schools, has been to request that it also be presented to freshman chemistry classes as a career-guidance service. This we have done. In addition to these activities we mail notices to a large number of chemistry departments and individual students as listed in the ACS lists of students recommended for graduate work.

All participants in the special summer class are expected to provide their own financial support. Our experience with all classes taught to date indicates that this is not a deterrent factor. The ChE department faculty decided that this special summer course should also serve as a screening mechanism to sift out marginal students. Therefore, all students entering the summer program are considered to be provisional students and are not admitted to full degree seeking status until they successfully pass the special course with a grade of B or better. Once a student successfully passes the special summer course, he is admitted

**In order to maintain quality
and a fundamental basis for such a
program the chemist must be taught fluid mechanics,
heat and mass transfer, and separations technology,
as well as kinetics, plant design, and process
synthesis and control.**

TABLE 4
Brief Course Descriptions

COURSE NO.	DESCRIPTION
464	Undergraduate plant design
478	Undergraduate kinetics
550	Process Synthesis
551	Process Control
672	Advanced Fluid Mechanics
673	Heat/Mass Transport
675	Advanced Thermodynamics
676	Advanced Separations
677	Creativity
681	Advanced Kinetics/Catalysis
691R	Graduate Seminar
693R	Special UO Course for Chemists
699R	MS Research/Thesis
CS 131	Elementary FORTRAN Programming
Math 321	Ordinary Differential Equations

to full degree seeking status and is treated exactly as any other graduate student. He is fully eligible for all forms of department financial aid.

An administrative concern for any program such as this is its cost to the university. Some programs [1], because of the heavy use of scholarship subsidies, auxiliary text material production, and administrative and faculty costs are relatively expensive. Our experience to date has indicated a much lower cost for our program. Because no student financial aid is given, the principal costs are for recruiting, which is nominal, and faculty and administrative costs. This program costs the ChE department something between \$5000 to \$6000 per year.

BACK TO BASICS

IN DEVELOPING THIS program we had to face the problem of what to teach a chemist to bring him "up to speed" in a short period of time so that he could successfully compete with ChE undergraduates in the advanced level courses. One possible approach, used by Carnegie-Mellon [1], is to give the chemists a brief introduction to each topic in the full undergraduate curriculum without going into detail or depth in any topic. In addition to lack of substantive depth, this approach creates the additional problem of what to use for

text material [1] necessitating the writing and reproduction of large amounts of hand-out materials, thus increasing costs. We chose not to take this route. Rather, we elected to develop a substantive course in unit operations in which the chemists could learn the fundamentals of fluid mechanics, heat and mass transfer, and separation technology at a level and depth commensurate with undergraduate ChE's. The special summer course which we have developed seems to accomplish this objective.

A second objective which this course must meet is to help the chemist overcome what might best be described as a "culture shock", which all seem to experience in making the transition from chemistry to ChE. Chemists do not approach problems in the same manner as do ChE's. The heavy emphasis on quantitative results, the need to make assumptions, and the necessity for manipulation of multiple systems of units are foreign concepts for most chemists and mastery of these skills is difficult for all and mildly traumatic for some. Most students generally accomplish this transition reasonably well during the first weeks of the course.

In order for the course to succeed both the instructor and the students must reconcile themselves to the idea that it requires full-time effort. Students are not allowed to register for any other courses and are permitted to engage in part time employment only in extreme circumstances.

The course is structured around the classical unit operations approach and closely follows the text *Unit Operations of Chemical Engineering*, 3rd Edition by McCabe and Smith [3]. This text has proved quite satisfactory for this course. Having a text available greatly helps the students and also reduces the overall costs of the program by eliminating the need for reproducing large amounts of handout materials. Table 5 contains a listing of the chapters and topics from the text which are covered during the course and the approximate amount of time spent on each. Short chapters are covered in one day while longer chapters require two days. As can be seen, all the material on fluid mechanics and heat transfer in

We further believe that graduates of our program can legitimately classify themselves as ChE's because they have had exactly the same graduate coursework and thesis experience that regular ChE's do plus most of the technical undergraduate experiences. They are not just "warmed over" chemists.

sections 2 and 3 of Reference three, and most of the material on mass transfer and separations processes in section 4 is covered. Section 5 on grinding, mixing and solids handling is omitted.

The class consists of from two to three hours of lecture each day starting at 8:00 A.M. Three or four homework problems are assigned each day which require most of the student's time following the lecture classes. The instructor frequently assists students in his office during this time. At 4:00 P.M. the class meets together with the instructor and a graduate teaching assistant for a problem solving session that may last from one to two hours.

Starting about the third week of the course one day a week is devoted to the laboratory. On lab day no lecture is held and students spend six hours in the lab. They see this as a welcome break from the routine of lectures and problem sessions of the other four days. In the laboratory the students are divided into two-man teams. Each team performs one experiment in each of the three subject study areas: fluid mechanics, heat transfer, and separations. Since there are a large number of experiments available in the BYU undergraduate unit operations lab and a small number of student teams, no two teams perform the same experiments. Each team is required to report orally to

TABLE 5
Topics Covered in Class

SUBJECT	NUMBER OF 2-3 HR. LECTURES
Material & Energy Balances	1
Fluid Statics	1
Introduction to Fluid Flow	1
Flow of Incompressible Fluids in Ducts	2
Flow of Compressible Fluids	1
Flow Past Immersed Bodies, Settling, Packed Beds, etc.	1
Pumping & Metering of Fluids	1
Mixing and Stirring Fluids	1
Conductive Heat Transfer	1
Fundamentals of Heat Transfer in Fluids	1
Heat Transfer to Fluids w/o Phase Change	2
Heat Transfer to Fluids with Phase Change	1
Radiative Heat Transfer	1
Heat Exchangers	2
Evaporation	1
Phase Equilibria, Diagrams, etc.	1
Equilibrium Stage Operations	1
Distillation	3
Leaching & Extraction	1
Multicomponent Distillation	1
Gas Absorption	1

... chemistry majors can successfully complete our program ... and are well qualified to go on to doctoral degree programs in ChE at reputable schools or go to work in industry.

the combined class on the experiment which they performed and to prepare written reports which are graded. This activity allows all students to become acquainted with each experiment and provides a good experience for the students preparing and giving the reports. This schedule is maintained for the remainder of the eight-weeks course.

RESULTS OF THE PROGRAM

THE PACE OF THE summer course is very demanding but student morale is generally quite high and the students develop a sense of achievement. Most students negotiate the chemistry to engineering culture shock quite well and are able to compete successfully with their regular ChE colleagues in subsequent graduate courses. About 80% of those starting in the program successfully complete it. To date we have had four graduates of this program accepted into doctoral ChE programs—two at BYU and two at other schools. Offers of employment have been about as frequent and as lucrative as those to regular ChE graduates. Indeed, some recruiters, notably from pharmaceutical companies, have specifically asked to see Biochemistry majors in the program. Thus, it seems that the students who complete this program are about as well qualified as regular MS ChE graduates to compete in the graduate school and job markets.

As with all programs, we have encountered some problems. The most serious problem is keeping the students from feeling overwhelmed during the summer course. Because of the large volume of material presented very rapidly, the students feel like they are always running behind trying to catch up. This problem is best handled by encouragement from the instructor and generous amounts of personal help. The class is limited in enrollment to 10-12 students so that the instructor can give the necessary amounts of personal help.

Another problem arises when students enter the program without prior background in ordinary differential equations or FORTRAN computer programming. This does not particularly cause problems during the special summer course. The

difficulties arise in the graduate fluid mechanics and thermodynamics courses which follow. As a result, poorly prepared students must follow a more protracted schedule shown in Table 3. About half of our students have encountered this problem. We are attempting to counteract this difficulty through our recruiting program by counseling junior chemistry majors who anticipate seeking admission to our program to take courses in ordinary differential equations and FORTRAN computer programming before they graduate.

Our experience to date indicates that chemistry majors can successfully complete this program for an MS ChE degree and are well qualified to go on to doctoral degree programs in ChE at reputable schools or go to work in industry. We believe that the combination of the intensive special unit operations course coupled with the full undergraduate senior year of ChE courses as a "supporting fields" graduate minor makes our program somewhat unique among the several programs now in existence. We further believe that graduates of our program can legitimately classify themselves as ChE's because they have had exactly the same graduate coursework and thesis experience that regular ChE's do plus most of the technical undergraduate experiences. They are not just "warmed-over" chemists. In our view this program represents a marriage of the best parts of both worlds. □

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1. Cussler, E. L., *Chem. Eng. Education*, 11 (4), 176 (Fall 1977).
2. Bethea, R. M., Heichelheim, H. R., and Gully, A. J., *Chem. Eng. Education*, 11 (4), 181 (Fall 1977).
3. McCabe, W. L., and Smith, J. C., *Unit Operations of Chemical Engineering*, 3rd. Ed., McGraw-Hill, New York, 1976.
4. Cussler, E. L., private communication to authors, 1977.



NEWS

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ChE news

MARATHON RUNNERS

Lloyd Berg reports that at least two chemical engineering department heads completed 26-mile marathons during 1978. Lloyd Berg of Montana State ran the Governor's Cup race in Helena and Tom Owens of North Dakota University completed the Grand Forks run. Any other department heads? Any other chemical engineering faculty?

LARSON SELECTED AS CHAIRMAN

The Department of Chemical Engineering at Iowa State University is pleased to announce that Dr. Maurice A. Larson has been selected as the new Department Chairman. Dr. Larson is currently Anson Marston Distinguished Professor in Engineering and has been a member of the Chemical Engineering faculty at Iowa State since 1958.

ChE books received

Continued from page 19

Solar Cooling and Heating: Architectural, Engineering and Legal Aspects, edited by T. Nejat Veziroglu. Hemisphere Publishing Corp., Washington, D.C. 20005. Three Volumes, \$120

The Chemical Bond, by J. N. Murrell, S. F. A. Kettle, and J. M. Tedder. Wiley, New York. 1978. 310 pages, \$27.

Recent Developments in Boiling and Condensation, by E. R. F. Winter, H. Merte, Jr., and H. M. Herz. Verlag Chemie International, New York. 1977. 106 pages paperback \$16.

Thermal Effluent Disposal from Power Generation, edited by Zoran P. Zoric. Hemisphere Publishing Corp., Washington, D.C. 20005. 1978. 375 pages, \$40.

Two-Phase Transport and Reactor Safety, edited by T. N. Veiroglu and S. Kakac. Hemisphere Publishing Corp., Washington, D.C. Four volumes, 1416 pages.

Fuel Economy of the Gasoline Engine, edited by D. R. Blackmore and A. Thomas. Halsted div. John Wiley, New York. 1977. 268 pages.

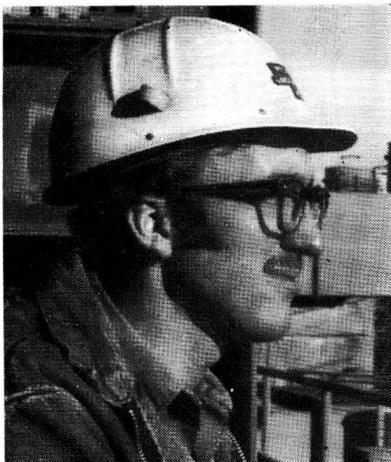
Two-Phase Flows and Heat Transfer, edited by S. Kakac and F. Mayinger. Hemisphere Publishing Corp., Washington, D.C. Three volumes, 1469 pages.

Engineering Fundamentals: Examination Review, 2nd ed., by D. G. Newnan and B. E. Larock. Wiley—Interscience, New York. 1978. 503 pages, \$21.95

Combustion and Incineration Processes: Applications in Environmental Engineering, by W. R. Niessen. Marcel Dekker, New York. 1978. 384 pages, \$35

Integrodifferential Equations and Delay Models in Population Dynamics, by J. M. Cushing. Springer-Verlog, New York. 1977. 196 pages \$8.30

Technical Data on Fuels, ed by J. W. Rose and J. R. Cooper, 1977. Halstead Division of J. Wiley, New York. 343 pages \$70



Loren Schillinger

B.S.Ch.E. from Montana State University in 1975 . . . joined FMC's Industrial Chemical Group plant at Pocatello as a process engineer in the technical department . . . involved in pilot project working with a fluid bed dryer to see whether a byproduct from the plant's production process could be used to fuel this vessel . . . worked with production, maintenance and engineering groups to gain better production efficiency throughout plant . . . promoted to unit foreman, supervised hourly workers in the preparation department . . . now planning analyst in the Phosphorus Chemical Division at Industrial Chemical Group headquarters . . . responsibilities include working on economic analyses of plant expansion to ensure that they are consistent with the Division's long-range plan; also conducts feasibility studies on the effect of proposed marketing changes on plant production equipment . . . says, "What really impresses me about FMC is the fact that a person is judged both on technical competence and on ability to work with others."



Mary Ann Pizzolato

B.S.Ch.E. from Rutgers University in 1976 . . . joined Industrial Chemical Group's Carteret plant as a process engineer . . . worked as engineer for the acid plant—did troubleshooting, process review and some pilot and new project work . . . promoted to assistant area supervisor in production department . . . works directly with area supervisor to ensure high quality and maximum production levels . . . likes having the opportunity to gain experience working with management and hourly workers . . . believes that "with the pressure to get production out as scheduled, you have to learn to work well with these groups—it's the best kind of on-the-job-training."

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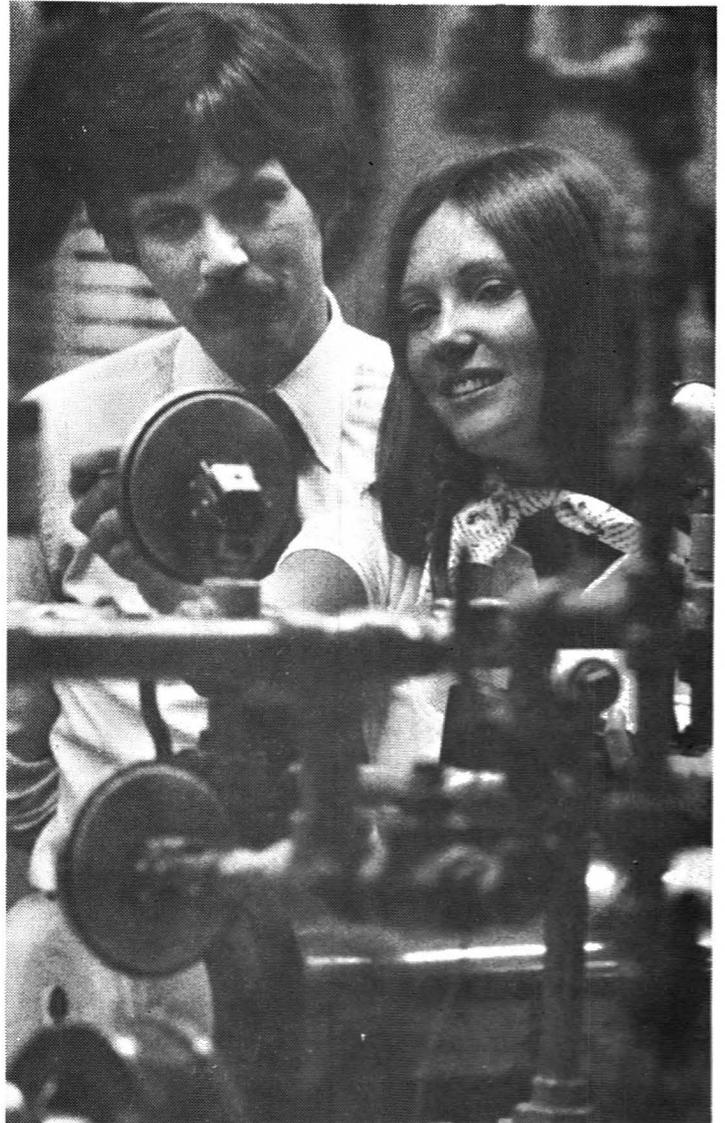
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