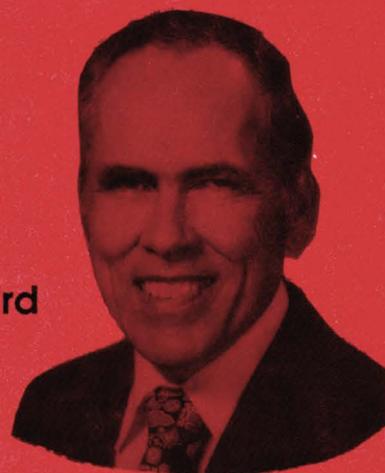




Warren Stewart

...of Wisconsin

by R. B. Bird



Accreditation
SLEICHER

Lubrication Flows
PAPANASTASIOU

Design Education In Chemical Engineering
DOUGLAS, KIRKWOOD

Experiencing Team Responsibility in Class
RHINEHART

An Experiment in Autotrophic Fermentation
SUBLETTE

An Alternate Approach to the Undergraduate Thesis
AMYOTTE, FELS

A Course to Examine Contemporary Thermodynamics
LEE

Unsteady-State Heat Transfer Involving a Phase Change
SUNDBERG, SOMESHWAR

Cheating Among Engineering Students: Reasons for Concern
TODD-MANCILLAS, SISSON

and ChE at...

RENSSELAER

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Warren E. Stewart of Wisconsin

R. BYRON BIRD
*University of Wisconsin
Madison, WI 53706-1691*

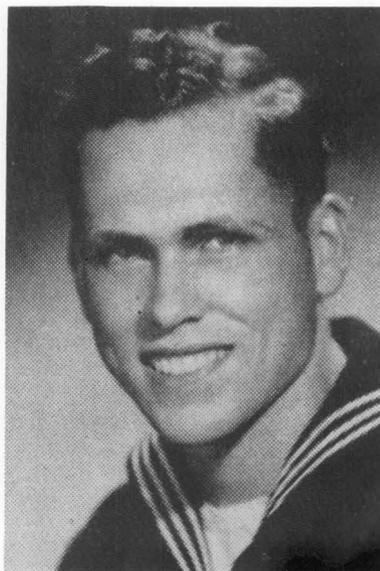
Warren received his BS and MS in chemical engineering at the University of Wisconsin in 1945 and 1947 respectively, and then he migrated eastward to study at MIT, where he received his ScD in 1951. I started graduate school at Wisconsin in 1947 and just missed meeting Warren then. However I heard many tales about him from the chemical engineering students at the AXΣ house who had been classmates of his. They uniformly sang his praises and mentioned time and again what a brilliant student he was, how they always got help from him on difficult homework problems, and that he was the first person to go through the undergraduate chemical engineering curriculum with a straight-A average. Within a few months he had become a legendary figure, and it was with this mythical Warren Stewart that I became acquainted in 1947.

In 1948 I took Joe Hirschfelder's course in quantum mechanics. Joe assigned Pauling and Wilson as the text for the course but said that we might find it helpful to study some mimeographed materials that he distributed to the class. These were Warren Stewart's notes of Joe's lectures in 1946, and Joe said they were much better than his own. So my next encounter with Warren was by studying quantum mechanics from his careful transcriptions of Joe's lectures.

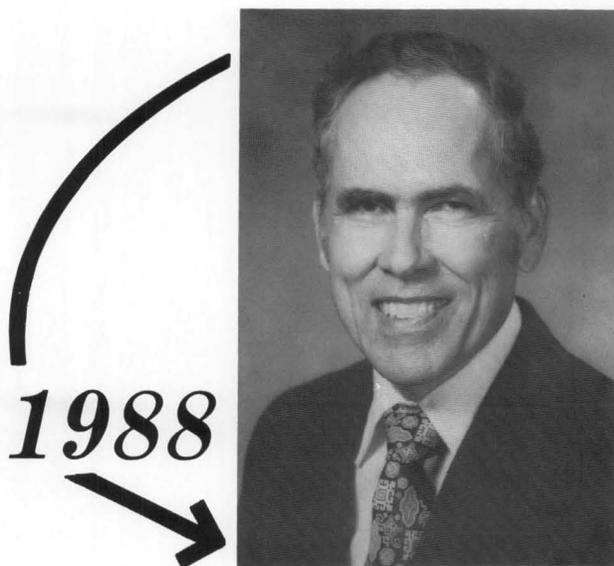
After graduate work at MIT, where he did his thesis on heat, mass, and momentum transfer, Warren became a Project Engineer at Sinclair Research,

... in 1960 the hardback textbook *Transport Phenomena* appeared. Warren was a superb contributor to the project for a number of reasons: he has exceptionally high standards for teaching and writing; he has a photographic memory of where things are in the literature; he insists on accuracy.

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1945



1988

Inc., in Harvey, Illinois. There he participated in the development of a catalytic reforming process and also in early work on computerized process simulation.

In 1953 I joined the chemical engineering department staff at UW. Here Warren's name came up often in conversations when faculty members recalled how scary it was to teach classes in which both Warren Stewart and Ed Daub were present (Ed was another legendary figure whose scholastic performance and keen mind had dazzled both staff and students).

In 1956 I finally had the chance to meet Warren, when he came to the department to interview for an assistant professorship that had opened up; shortly thereafter he joined our faculty. This was the beginning of a long friendship which I have very much valued through the years. Warren lived up to the legend, and more. I found him to be a great scholar with an awesome grasp of science and engineering, as well as a compassionate teacher, a dedicated family man, and a marvelous raconteur of jokes. Those who see only

the serious side of Warren don't realize that his repertoire of jokes, puns, and conundrums is every bit as impressive as his uncanny ability to solve complex scientific problems.

By 1957 Warren Stewart, Ed Lightfoot, and I had joined forces to prepare mimeographed material for a new course on transport phenomena. This occupied much of our time in the fall of 1957 and the spring of 1958; our green paperback book, *Notes on Transport Phenomena*, was published by Wiley in the fall of 1958 as a "preliminary edition." Then we spent another two years revising the "Notes," and in 1960 the hardback textbook *Transport Phenomena* appeared. Warren was a superb contributor to the project for a number of reasons: he has exceptionally high standards for teaching and writing; he has a photographic memory of where things are in the literature; he insists on accuracy; he is a meticulous proofreader (his ability to detect the smallest of errors earned him the nickname "Gimlet-Eye"); and—very important in book-writing—he has a wonderful sense of humor. During the manuscript preparation I felt that I was continually learning about transport phenomena from Warren (just as I had learned quantum mechanics from him a decade earlier). He had had, after all, a lot of experience in transport phenomena in boundary layers during his thesis work at MIT as well as some five years of practice in solving industrial problems. That period of intense work, 1957-1960, formed particularly strong bonds within the triumvirate—bonds that have survived for many years.

A few years later Warren started studying Spanish, an effort which has given him another "dimension." He has made Latin America his primary overseas field of interest. He provided assistance to the translator who prepared the Spanish Edition of *Transport Phenomena*. He was a Visiting Professor at the Universidad Nacional de la Plata (Argentina) in 1962, and a Visiting Lecturer at the Instituto Tecnológico de Celaya (México) in 1983 and at the Universidad Nacional Autónoma de México in 1985. He has also given seminars (usually in Spanish) at a number of other Latin American institutions. It is rare for engineering professors to take the trouble to learn another language well enough to be able to lecture in it. Of course, this carries with it certain dangers. Warren attained instant fame in Mexico because of a linguistic blunder he committed in a lecture at the Instituto Tecnológico de Monterrey. Someone in the audience asked him a question to which he unfortunately didn't know the answer. So he wanted to say to the audience something like, "I'm very embarrassed that I don't know the answer to that question." Now when

A few years later Warren started studying Spanish, an effort which has given him another "dimension." . . . He provided assistance to the translator who prepared the Spanish Edition of *Transport Phenomena*.



Warren and Jean (bottom row) in 1982 at a family gathering.

we speak foreign languages we often encounter words that are not in our vocabulary and so we make a guess and hope the listeners will understand. This works pretty well for an English speaker talking Spanish. Warren didn't know the word for "embarrassed" but boldly produced the sentence "Estoy muy embarazado, que no se la respuesta a ese pregunta" (instead of "Es embarazoso, que. . ."). Well, it turns out that "estoy muy embarazado" means "I am very pregnant." Understandably the audience exploded with laughter. (See what fun you miss out on if you don't try learning a foreign language!) This story popped up in a limerick read at Warren's 60th birthday party on July 2, 1984:

*He tackles tough tasks with bravado
With the verve of a wild desperado—
But he's really quite droll
When he talks español
And says that he's "embarazado."
Anne Nonimus*

Despite his occasional problems with Spanish, Warren has for several decades administered the departmental PhD Spanish reading exam. He and his wife Jean, (who for many years has been the "alderperson" for Madison's 20th District), have often shared the hospitality of their home with visitors from Latin America (and from other parts of the globe as well). They and their children have been gracious hosts on many occasions, and countless visitors will long remember their pleasant evenings at the Stewart home.

Warren's linguistic accomplishments are not restricted to Spanish. He is also very fluent in "Alfalfa."

This is a pig-Latin-like way of speaking where you insert "LF" in the middle of the predominant vowel in each word; thus "seem" transforms into "seelfeem." Since I also learned "Alfalfa" as a youngster, Warren and I often carry on long conversations in our "secret language" much to the astonishment of bystanders. Warren can even speak Alfalfanized Spanish!

But, we digress. Let's get back to Warren and chemical engineering. Warren is one of the most versatile people that I know. I think he has taught almost every course in the department. His list of research publications is also characterized by great diversity. How many chemical engineers could write significant contributions on such widely varying topics as prediction of vapor pressures; reciprocal variational principles; kinetics of benzene hydrogenation; multicompo-

nent diffusion; orthogonal collocation; measurement of diffusivities; droplet vaporization; kinetic theory of rigid-dumbbell suspensions; tokamak reactors; thermal diffusion; catalysis; corrosion; parameter-estimation; Bayesian statistics; viscoelastic fluid dynamics; sensitivity analysis; and distillation column design? Whereas most professors work in rather narrow areas, Warren has been an impressive generalist. When he was chairman of the chemical engineering department (1973-1978), he was able to discuss details of research projects being carried out by all of his departmental colleagues; no other chairman before or since has been able to do that. This was one of his great strengths when he served the department so ably as our chairman.

Warren's enormous breadth of interest has re-

STEWART'S TOP TEN

1. Forced Convection in Three-Dimensional Flows: I. Asymptotic Solutions for Fixed Interfaces, by W. E. Stewart, *AIChE Journal*, **9** 528-535 (1963). This deals with the prediction of heat and mass transfer in thin boundary layers at rigid interfaces, with given interfacial shape and velocity gradient. A prediction of the Nusselt number for a packed bed is given. The importance of this paper was not widely appreciated until the publication of [6] eleven years later.

2. Matrix Calculation of Multicomponent Mass Transfer in Isothermal Systems, by W. E. Stewart and R. Prober, *Ind. Eng. Chem. Funds.*, **3**, 224-235 (1964). This paper (and another that year by Herb Toor at CMU) showed how to solve a large class of multicomponent mass-transfer problems realistically by transforming the problem to a set of binary problems; this method is used extensively in the current literature on distillation and absorption.

3. Solution of Boundary-Value Problems by Orthogonal Collocation, by J. V. Villadsen and W. E. Stewart, *Chem. Eng. Sci.*, **22**, 1483-1501 (1967); *ibid.*, **23**, 1515 (1968). This paper (which was designated as a "Citation Classic" in *Current Contents* on 9/21/81) has been widely adopted by reactor designers for calculating radial profiles in reactor tubes and catalyst particles. This method of computation combines the simplicity of collocation with the efficiency of orthogonal polynomial interpretation.

4. Forced Convection in Three-Dimensional Flows: II. Asymptotic Solutions for Mobile Interfaces, by W. E. Stewart, J. B. Angelo, and E. N. Lightfoot, *AIChE Journal*, **16**, 771-786 (1970). Here single-phase transfer coefficients in fluid-fluid contactors are related to the fluid properties and interfacial motion. This theory should eventually supplant the penetration and surface-renewal theories, and it includes time-dependent and turbulent flows. Comparisons with experiment show good agreement.

5. Practical Models for Isothermal Diffusion and Flow in Porous Media, by C. Feng and W. E. Stewart, *Ind. Eng. Chem. Funds.*, **12**, 143-146 (1973). This paper gives extensive data on 3-component diffusion in catalyst pellets and thereby tests several diffusion models; it has been widely cited in works on realistic modeling of catalyst particle performance.

6. Computation of Forced Convection in Slow Flow Through Ducts and Packed Beds, by J. P. Sørensen and W. E. Stewart,

Chem. Eng. Sci., **29**, 811-837 (1974). In this 4-part pioneering study the fluid dynamics and mass-transfer processes in regular packed beds are studied. Impressive agreement with experiments is found for the appropriate ranges of Reynolds and Peclet numbers.

7. Computer-Aided Modelling of Reaction Networks, by W. E. Stewart and Jan P. Sørensen, in *Foundations of Computer-Aided Process Design* (R. S. H. Mah and W. D. Seider, Eds.), Vol. II, Engineering Foundation, New York, 335-366 (1981). This survey paper summarizes the work of Warren's group on digital analysis of reaction models and on parameter estimation from multiresponse reactor data. "Expert" programs are provided for use by kinetics researchers. The programs automatically evaluate reaction schemes for their fit of data and then estimate the parameters that are determinable from the data given.

8. Simulation of Fractionation by Orthogonal Collocation, by W. E. Stewart, K. L. Levien, and M. Morari, *Chem. Eng. Sci.*, **40**, 409-421 (1985). Whereas in [3] above Jacobi polynomials were found to be optimal for continuous systems, here it is shown that for discrete systems Hahn polynomials should be used. Hence, stagewise processes can be analyzed and designed very effectively.

9. Sensitivity Analysis of Initial-Value Problems with Mixed ODEs and Algebraic Equations, by M. Caracotsios and W. E. Stewart, *Comput. Chem. Eng.*, **9**, 359-365 (1985). This work gives an efficient method for computing the sensitivity of a process model to its parameters. The algorithm is implemented on a modern differential-algebraic equation solver and is illustrated by a reaction modeling problem. Sensitivity calculations are widely useful in modeling, control, and optimization.

10. Forced Convection: IV. Asymptotic Forms for Laminar and Turbulent Transfer Rates, by W. E. Stewart, *AIChE Journal*, **33**, 2008-2016 (1987); **34**, 1030 (1988). Here "dominant-balance arguments" are used to get information about heat and mass transfer rates without integrating any differential equations. New results are obtained for turbulent flows, and this work supplements [1] and [4] above. The celebrated Chilton-Colburn j -factors correspond to the leading term of the long-time expansion.

sulted in the fact that he frequently functions as an "in-house consultant" to colleagues and students in chemical engineering as well as from other departments. It's not unusual to see him conferring in his office with a professor of zoology on heat transfer through fur, with a student from nuclear engineering on a problem related to controlled nuclear fusion, or with a chemical engineering graduate student on viscoelasticity. I've never heard of an undergraduate or graduate student ever being turned away by Warren. His door is always open for interruptions, and he has always been very generous with his time and very patient with his "customers." His willingness to help others by sharing his talent is the subject of this bit of doggerel:

*A student came in to see Warren
And said in a voice quite forlor'n
"I can't find a path
Through this quagmire of math;
These nablas are terribly foreign."
So Warren (who's also called Earl)
Proceeded to help this young girl.
Without using a book
He unflinchingly took
The Laplacian of grad div curl curl.
Anne O. Nimes*

Well now you know what the "E" stands for in Warren E. Stewart.

All researchers have publications of which they are especially proud. Warren feels that the box on the opposite page lists his ten best research publications. He is currently working on the manuscript of a book on computer-aided modeling of reacting systems which promises to be a thorough, scholarly, and useful work.

Warren is a quiet and modest person. He never talks about the many awards that have come his way, including honorary membership in Phi Beta Kappa, the ASEE Chemical Engineering Lectureship Award, the Alpha Chi Sigma Award and the Computing in Chemical Engineering Award of AIChE, the Benjamin Smith Reynolds Teaching Award at UW, and the McFarland-Bascom Professorship at UW. In 1989 he will receive the Murphree Award of ACS. He should also receive a special award for being able to meet deadlines in a photo-finish. At 10:59 am he can be seen frantically xeroxing materials for an 11:00 am class. At 11:59 pm on April 14th he can be seen speeding up to the main post office in Madison with his income tax return. And I recall the time when several of us decided to see Warren and his family off at the airport when they were headed for the Middle East where Warren was to give some lectures. At 10 minutes before plane time, the Stewarts were still not at the



Warren takes time out of a typically busy day to welcome a visitor.

airport; at -5 minutes still no sign of them; at -2 minutes they scrambled out of a taxi cab and they *did* make the plane. Apparently Warren thrives on the excitement of seeing how close he can come to not quite missing a deadline.

One of Warren's most outstanding contributions has been the development of the powerful technique of "orthogonal collocation," and according to Harmon Ray it is probably one of the most significant original contributions to numerical analysis ever made by a chemical engineer. Here again, this activity has been memorialized in a poem inflicted on the audience at Warren's 60th birthday party:

*He's often referred to as "WES".
He's known from Rangoon to Loch Ness
For fast collocation
In flash distillation—
And multicomponent, no less!
U. N. Bekannt*

No doubt about it—Warren has had a distinguished career. And he is still going strong with a very active research program, book-writing activities, consulting, memberships on editorial boards, public and community service activities, and music (he plays the trombone!). He has certainly earned a place in the "ChE Hall of Fame."

ACKNOWLEDGEMENT

Many thanks to ENL, EED, WHR, and REF for constructive criticisms of the original manuscript. □

RENSSELAER POLYTECHNIC INSTITUTE

MICHAEL M. ABBOTT
Rensselaer Polytechnic Institute
Troy, NY 12180

Rensselaer Polytechnic Institute was founded as the Rensselaer School in 1824, "for the purpose of instructing persons who may choose to apply themselves in the application of science to the common purposes of life." It has evolved into a university comprising five schools, 400 faculty and full-time researchers, and 6400 students. Of the latter, approximately 1900 are graduate students.

Chemical engineering at Rensselaer began seventy years ago as a program in the Department of Chemistry. In 1943, it became a separate academic unit, with Lewis S. Coonley as its first head. It is now one of the eight departments and five centers which compose the School of Engineering. Chemical engineering has eighteen active faculty members; another three from other departments hold joint appointments with us. Undergraduate enrollment is approximately 175, and graduate students number about 60, with 75% pursuing the PhD.

We have a building largely to ourselves. Separated by a comfortable 100 yards of football field from the Engineering-School administration, the Ricketts Building is our home. Ricketts contains offices, classrooms, a unit-operations laboratory, and about 14,000 square feet of research laboratories. An in-house electronics/machine shop is available for use by students and staff.

The perceived heart of a contemporary engineering department is the range and strength of its research interests. In that respect, chemical engineering at Rensselaer is fortunate to have coverage in many areas . . .

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Our research labs are relatively new, the result of an extensive renovation undertaken in 1978. Since then, a central graduate-student office/study area has been constructed and furnished. Most recently, through the generosity of Howard Isermann (a Rensselaer chemical engineering alumnus), we have been able to renovate and outfit 3000 square feet of new laboratory space for our biochemical engineers. This facility will help us to compete successfully with other first-class programs in biochemical engineering.

BREADTH AND DEPTH

The perceived heart of a contemporary engineering department is the range and strength of its research interests. In this respect, chemical engineering at Rensselaer is fortunate to have coverage in many areas: air resources, advanced materials, biochemical engineering, control and design, fluid-particle systems, interfacial phenomena, kinetics and reactor design, polymer engineering, separation processes, thermodynamics, and transport processes. A special pride is our biochemical engineering group, with a critical mass of three (approaching four) specialists.

Interdisciplinary interactions are currently encouraged at Rensselaer, and chemical engineering benefits from numerous collaborations. Belfort works with Don Drew from mathematics, Gill with Marty Glicksman from materials engineering, and Nauman with various polymeric enthusiasts from chemistry and materials engineering. Rensselaer's Center for Integrated Electronics provides one of several foci for those (*e.g.*, Gill, Wayner) with interests in advanced materials. Belfort,

E



Home Sweet Home: The Ricketts Building. Local legend has it that Palmer C. Ricketts (a former Rensselaer president) is interred behind his memorial plaque in the foyer. On moonless nights, his shade perturbs unattended experiments.

Littman, Morgan, and Wayner are members of the Center for Multiphase Flow; Belfort, Bungay, Cramer, Gill, Morgan, and Nauman, of the Bioseparations Research Center; and Cramer, of the Biophysics Research Center. And the Department of Electrical, Computer, and Systems Engineering harbors like-minded souls with whom Bequette exchanges ideas on process dynamics and control.

What makes academic research "go"? Money, of course, and a dedicated and energetic faculty. We, like others in this business, must scramble for the former. The latter, fortunately, is a given. Our research environment is healthy; we are better than competitive, and yearly attract a strong group of graduate students. Problems of student support are mitigated by fifteen new Isermann Graduate Fellowships which are endowed in perpetuity.

FACULTY SNAPSHOTS

R. H. Wentorf is Distinguished Research Professor of Chemical Engineering. Bob is inventor or coinventor of techniques for commercial production of very hard materials (Borazon, diamond). He has many technical interests, ranging from polymer-fiber fabrication to semiconductor processing. After-hours, Bob is a farmer and a glider pilot. **P. C. Wayner, Jr.** studies transport phenomena in evaporating menisci and in ultra-thin films. His arsenal of experimental tech-

niques includes scanning microphotometry and photo-scanning ellipsometry. For analysis, he uses capillarity concepts and London/van der Waals theory. Pete enjoys tennis and skiing. **H. C. Van Ness** is Institute Professor of Chemical Engineering. He specializes in the measurement, reduction, and correlation of thermodynamic properties of liquid mixtures. Hank's equipment designs have been widely adopted, and are the source of many of the world's heat-of-mixing and VLE data. Hank golfs and plays the piano.

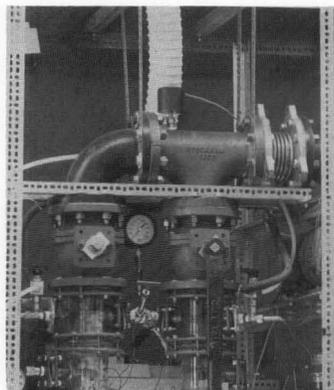
J. L. Plawsky works with optical substances. He seeks to understand how the various transport phenomena affect the processing of wave-guide devices. Related interests include developing novel materials based upon inorganic/organic copolymer systems and investigating complex mixing effects in flowing glasses. Joel plays rock guitar and swims. **E. B. Nauman** is director of the Industrial Liason Program for chemical engineering. His principal research interests are in polymer processing and polymer-reaction engineering. Much of his current work relates to the compositional-quenching process, which he invented. Bruce characterizes his hobby as "pure and applied flamboyance"; he is the only R.P.I. prof whose winter car is a Jag XJS. **C. Muckenfuss** shepherds our seniors through the final year of chemical engineering; he is responsible for their advising and eventual clearance. His research centers on first-principle studies of trans-



Bruce Hook adjusts a data point. Behind him: Littman's cat combustor, a.k.a. High-Temperature Gas-Phase Spouted-Bed Catalytic Reactor.

port phenomena, *i.e.*, on the application of kinetic theory and irreversible thermodynamics to multicomponent, reacting systems. Charlie is an avid bicyclist/traveler.

M. H. Morgan III works with fluid/particle systems. His current research focuses on the development of reactor theories and of fluid-mechanical models for spouted beds with draft tubes. Experimental and theoretical studies abound. Morris is a serious competitive runner: in 1988 he took a Submaster's gold medal with a 2:03 half-mile in New York's Empire State Games. **H. Littman** conducts basic research on gas/liquid and fluid/particle systems. Ongoing efforts include studies on the dynamics and control of spouted-bed reactors, pneumatic transport of fine particles, and jet stability and the transition to bubbling. Howard is a 1988 recipient of Rensselaer's Distinguished Faculty Award. He hikes and runs for fun.



Nauman's compositional quencher. Bruce probes the depths of the spinodal region, seeking to produce rubber-modified polymers with controlled particle-size distributions.

"Fringe benefits": Wayner's scanning ellipsometer with interferometer and laser light source. Mounted on a vibration-proof table, it is immune to the shocks of Ricketts's frequent renovations.



P. K. Lashmet is Executive Officer of chemical engineering. His research concentrates on process engineering and on the improvement of basic design procedures. Currently, he explores the effects of parameter uncertainties and process variations on non-dynamic equipment performance, employing Monte Carlo simulation techniques. P.K. enjoys his family and power-boating (in that order).

W. N. Gill is Head of chemical engineering; his research is in the applied transport areas. Current efforts include studies in membrane separation techniques and the design and modeling of chemical vapor deposition reactors. Of special interest are experimental and theoretical investigations of dendritic growth of ice and of succinonitrile, and the non-linear dynamics of pattern formation in crystal-growth systems. Bill likes films (classic and foreign), music, plays, running, and martinis. **A. Fontijn** studies combustion. The major efforts of his group concern the high-temperature reaction kinetics of combustion intermediates. For the experimental studies, Fontijn has developed special fast-flow and pseudostatic thermal reactors. Arthur hikes and travels for relaxation. **S. M. Cramer** specializes in biochemical engineering. His interests

"As soon seek ice in June": Bill Gill does. This dendrite began life as a smooth disk. Bill studies its evolution with digital image analysis, and predicts its development with theory.



An unattended experiment? Not to worry. This machine (Cramer's new Delta Prep chromatographic unit) practically runs itself.

center on the synthesis and separation of biomolecules. Research efforts include experimental and theoretical studies of preparative chromatographic techniques (especially displacement chromatography), and enzymatic organic synthesis. Steve is an accomplished jazz pianist who performs regularly with High Society, a group of professional musicians.

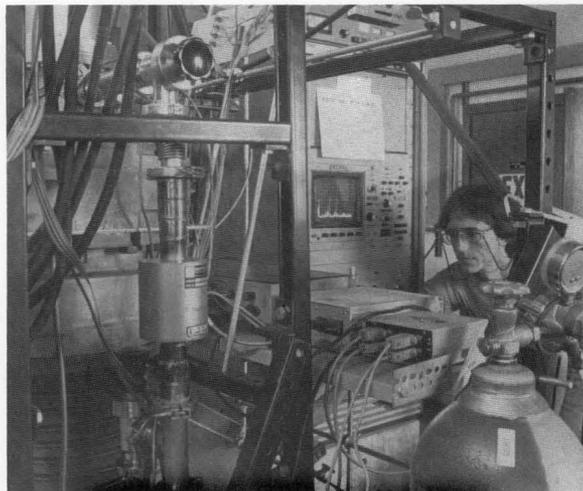
H. R. Bungay III conducts research into microbial growth and biomass refining. Capillary microelectrodes with tips a few microns in diameter are used to study oxygen transfer in various microbial systems. Intensive efforts are geared toward eventual commercialization of processes for conversion of wood chips to salable chemicals. Harry is a licensed pilot and a bridge Life Master. **W. D. Bradley** is an essential contributor to our undergraduate instructional program. He brings to us forty years of experience as a practicing chemical engineer. Bill's technical interests span the spectrum of design topics and focus on the ultimate questions: Will it work? Will it make money? His hobbies include beekeeping and herb-gardening. **B. W. Bequette** seeks to integrate the traditionally separate issues of modeling, design, optimization, and control into a consistent methodology. Emphasis is on applications to the manufacture of semiconductor devices. Nonlinear control theory is a special enthusiasm. Wayne's outside interests include collision theory and trajectory analysis (softball) and high altitude inefficient conversion of potential to kinetic energy (skiing with reckless abandon).

G. Belfort studies the fundamentals of synthetic membrane processes and applications of these processes to biotechnology. Fluid-mechanical concepts are used to analyze membrane particulate fouling and to develop rational design procedures. Flow cytometry and NMR imaging are among the experimental techniques employed in Belfort's work. Georges coaches soccer and plays squash. **E. R. Altwicker** works in selected areas of air pollution control and atmospheric chemistry. Current efforts include studies of S(IV) oxidation and of the heterogeneous combustion of waste fuels. A falling-drop reactor allows controlled investigation of scavenging and scrubbing operations, and complements theoretical studies of mass transfer with chemical reaction. Elmar skis and plays tennis and the violin. **M. M. Abbott** does thermodynamics. Technical interests include phase equilibria, solution thermodynamics, and the PVT_x equation of state. His professional passion is the classroom. Mike reads history, poetry, and music.

DISTINGUISHED COLLEAGUES

Outside recognition by one's peers is an indicator

**Is there professional life beyond the laboratory?
We hope so. Education is still our major business,
and service to the profession is a close second.
Van Ness, Cramer, Bungay, and Abbott have
all won major teaching awards: . . .**



Fontijn's HTFFR (pronounced "aitch-tuffer"), with Clyde Stanton at the controls. With this and other devices, Arthur studies gas-phase kinetics over humongous temperature ranges.

of the strength of a department, and we enjoy a share of such honors. In 1985, Fontijn received the ACS Award for Creative Advances in Environmental Science and Technology. Bill Shuster (just retired from Rensselaer) was a 1987 recipient of AIChE's Award for Service to Society. And 1988 has been an especially happy year for us, with Bungay obtaining the ACS Marvin J. Johnson Award in Microbial and Biochemical Technology and Van Ness receiving AIChE's Warren K. Lewis Award.

Four Rensselaer faculty (Bungay, Nauman, Van Ness, and Wayner) are AIChE Fellows. Wentorf is a member of the National Academy of Engineering. Gill, Littman, and Van Ness have done Fulbrights. Gill was the first Glenn Murphy Distinguished Professor at Iowa State University. In 1988, Belfort was Flint Scholar at Yale University, and Van Ness was Phillips Petroleum Company Lecturer at Oklahoma State University. And so it goes: we enjoy our share.

LAST, BUT NOT LAST

Is there professional life beyond the laboratory? We hope so. Education is still our major business, and service to the profession is a close second. Van Ness, Cramer, Bungay, and Abbott have all won major teach-

ing awards; Abbott has just finished a two-year stint as a Rensselaer Distinguished Teaching Fellow. We currently have in print ten textbooks and monographs: *Basic Engineering Thermodynamics*, 2nd Ed. (Zemansky, Abbott, and Van Ness); *BASIC Environmental Engineering* (Bungay); *Chemical Reactor Design* (Nauman); *Classical Thermodynamics of Nonelectrolyte Solutions* (Van Ness and Abbott); *Computer Games and Simulation for Biochemical Engineering* (Bungay); *Energy: The Biomass Option* (Bungay); *Introduction to Chemical Engineering Thermodynamics*, 4th Ed. (Smith and Van Ness); *Mixing in Continuous Flow Systems* (Nauman and Buffham); *Schaum's Outline of Theory and Problems of Thermodynamics* (Abbott and Van Ness); and *Understanding Thermodynamics* (Van Ness).

Several of us serve on AIChE technical programming committees. Most of us are members of one or more editorial boards. And, of course, Rensselaer is the home of *Chemical Engineering Communications*, edited by Bill Gill. CEC receives about 400 manuscripts each year, thus providing valuable interaction between Rensselaer and the international chemical engineering community.

Douglas R. Hofstadter asks if the soul of a collection of individuals can be greater than the hum of its parts. We believe so. With strong commitments to education, to professional service, and to research and scholarship, chemical engineering at Rensselaer is certainly a humming place. A diversity of styles and interests, a healthy dedication to the principle of lese majesty, and a sense of collegiality combine to provide our department with a lively atmosphere in which to pursue one's professional goals. It's a great place to work and study. □

ChE letters

LEVENSPIEL CLAIM DISPUTED

To the Editor:

We wish to reply to Dr. Octave Levenspiel's letter published in your Summer 1988 issue which erroneously compares *Chemical Engineering Science* with *Chemical Engineering Communications* as to both cost and price.

Doctor Levenspiel's analysis is incorrect in just about every respect imaginable. Unfortunately, the sorry business could have been avoided had Dr. Levenspiel verified his information with us prior to publication. I hope that in view of the facts as outlined below, he will retract his letter and save further embarrassment.

1. The subscription prices quoted by Dr. Levenspiel

for the present calendar year in his letter article are false. He quotes a price of \$296 for a volume. In fact the academic library rate is \$184, substantially less than *{sic}* the figure quoted in his letter. Furthermore, there is an individual subscription rate at 50% of the library rate, or \$92 per volume.

2. In a comparison, these rates are further reduced by the fact that our rates include airmail postage and handling charges all over the world, while in other publications, these costs may be added separately. So a comparable library subscription rate with a publisher who charged separately for these services, would be about \$25 lower or about \$169.

3. We did study a recent front matter of an issue chosen at random of *Chemical Engineering Science*. It was volume 43, number 7 of that publication. In that issue the 1988 institutional subscription rate for a single year is listed at 1400 DM. We telephoned a major subscription agent who today [August 24, 1988] advised us that the present price in dollars of an academic subscription was \$862.50, about twice as expensive as the rate of \$435 quoted in Dr. Levenspiel's letter. Incidentally, having chosen this particular article quite by chance, we were surprised that the lead article was the Third P. V. Danckwerts Memorial Lecture by O. Levenspiel and that the front matter included a photograph taken in May 1988 showing Dr. Levenspiel together with the Editorial Director of Pergamon Press as well as the Executive Editor of *Chemical Engineering Science*. We did not verify the other columns of pages and words per page as in Dr. Levenspiel's article but in view of the fact of the other distortions of price and size, we have no reason to accept these as being any less biased.

4. As to the change in format, there was a change in format of *Chemical Engineering Communications* but the amount of material offered subscribers per volume has always been adjusted and remained the same. The number of pages per volume was increased to compensate for the decreased amount of material per page for the change from a double-column to a single-column format. Dr. Levenspiel suggests that the change in format was made to deceive readers; this is simply untrue.

We have always published on a flow basis in that we estimate the number of pages and/or volumes for publication in the upcoming 12-month period. Rather than delay publication of articles to conform to a fixed number of pages, articles are published as ready for most rapid publication. In prior years, as the number of pages billed was reached earlier or later than anticipated renewals were either advanced or delayed accordingly. In the last two years, we have changed this policy so that issues are published on a calendar-year basis. The number of pages for the coming year is estimated and this determines the subscription price for that year. Should the number of pages be over or underestimated, the price is adjusted accordingly in the subsequent renewal period. In the year 1987, we overestimated the number of pages which would be supplied. Accordingly the subscription price for

1988 was reduced by 38% in the present subscription year. Each month, the number of pages ready for publication is published so that individual issues may vary widely in size. Thus a 250 page issue may be followed by a 1000 page issue in the next month, and so on. Any single issue which Dr. Levenspiel uses in his comparison is therefore likely to distort the results.

4. [sic] Furthermore, the comparison with *CES* is further distorted by other erroneous information. I cannot directly comment on the difference in subscriber bases and cannot comment on the differences in publication methods, except to say that unless a complete analysis of the subscriber bases and international markets are [sic] made, no cost comparison can be made. For example, a society publication, say, may have other sources of editorial funding such as page charges or distribution methods such as bulk society purchase would no doubt have other ways of generating revenue which would supplement the subscription price. Some publications accept advertising and are distributed on a controlled circulation basis, while others are not. In any event the scopes of the publication are quite different. *Chemical Engineering Communications* provides "a forum for the rapid publication of papers in all areas of chemical engineering." A recent issue of *CES* states in its scope "The object of the journal is to publish papers dealing with the application to chemical engineering of the basic sciences and mathematics...."

The other areas of distortion in a valid comparison can include such factors as complexity of typesetting and quality of materials. For example, *CEC* offers free publication of color photographs as well as other special services. In addition libraries subscribing to *CEC* can, for an additional nominal \$5 per volume receive a photocopy licence [sic] allowing them unlimited photocopying thus providing a very low cost of dissemination.

The true current cost to subscribers of *CEC* is about half of that quoted in Dr. Levenspiel's letter and compares favorably with other commercial, international journals. In a major pricing study recently prepared by a major university library system our company was ranked 18th.

In fact, we are quite concerned about the current library budget crisis. We have been trying for some time now to find a way to defer or lessen the effect of inflation and currency problems on our regular subscribers. We are enclosing a press release of a program which we are announcing to further reduce the costs to existing subscribers. Our prices, after adjustment for changes in numbers of pages, have increased only 10% in the last three years despite a higher inflation rate and a falling dollar. Unfortunately, damaging false analyses like Dr. Levenspiel's serve only to raise prices by reducing units, not to lower them.

We work in an intellectual area with intellectual product and try to orient our services to the needs of the community. Libelous attacks made without fact or

knowledge and without verification like those of Dr. Levenspiel serve no useful purpose in this enterprise.

Martin B. Gordon
Gordon and Breach, Science
Publishers, Inc.

Editor's Note: *The Press Releases enclosed with the above letter describe a "Subscriber Incentive Plan" (SIP) that would result in 10-20% discounts when certain conditions are satisfied. A basic membership earns a 10% discount which will be automatically granted for the 1988-89 period, with future discounts dependent on membership in SIP; a 5% discount voucher "credit memo" good on future renewals will be extended with enrollment in the SIP; and an additional 5% discount is offered to the subscriber if the order is placed through their preferred agent, STBS. The offer will initially be restricted to North American libraries.*

ChE book reviews

DIRECT CONTACT HEAT TRANSFER

by Frank Kreith and R. F. Boehm
Hemisphere Publishing Corp., 1988

Reviewed by
Joseph J. Perona
The University of Tennessee: Knoxville

The term "direct-contact heat transfer" denotes the physical contacting of media for heat exchange purposes in the absence of a separating barrier, such as a tube wall. Some applications are quite old, e.g., cooling towers and barometric condensers. The concept is not mentioned by such modern textbooks on heat transfer as those by Lienhard and by Incropera and DeWitt. A chapter is devoted to it in Kern's book, published in 1950.

Direct contact operations are fundamental to chemical engineering. Nearly all mass transfer processes are direct contact operations. From an analysis or modeling standpoint, direct-contact heat transfer is not significantly different from nonisothermal mass transfer, unless radiation is important. The state-of-the-art is the same. For transfer between fluid phases, interfacial areas are usually not known and experiments produce volumetric coefficients, in which the transfer coefficient and interfacial area are lumped together. Similar contacting devices are used. Since mass transfer inevitably accompanies direct-contacting, its extent must be evaluated in any heat transfer application. It may or may not be desirable for the objectives of the operation.

The primary advantages of direct-contact heat transfer over surface exchangers are the elimination of

Continued on page 30.

ACCREDITATION

Changes Are Needed

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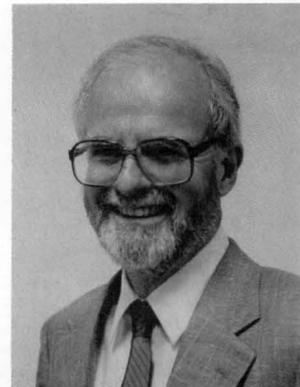
THE PRIMARY PURPOSE of accreditation of undergraduate engineering programs is to protect students by assuring a set of minimum academic standards. A secondary purpose is to protect the public, companies, governments, and professional engineers themselves from employment of ill-qualified individuals, which is to say anyone who graduates from a program that is not accredited. This purpose will always be secondary, for no program can guarantee the qualifications of every graduate. That is the purpose of licensing, whereas accreditation is simply the academic equivalent of the Good Housekeeping Seal of Approval.

There is a price to be paid for accreditation, and it is therefore appropriate to ask if we gain as much as we lose by the accreditation process and to examine what can be done to overcome some of the negative aspects of accreditation. The four principal benefits of accreditation to a department are:

- 1. It is an asset to enrollment. Students seek to enroll in accredited programs. (In some states one must be a graduate of an accredited program in order to take the E. I. T. exam.)*
- 2. Accreditation suppresses competition. Accreditation is usually necessary for survival of the program, but developing the resources necessary for accreditation is expensive and, therefore, not easily undertaken.*
- 3. Accreditation protects its graduates from quacks, charlatans, and graduates of non-accredited programs who*

. . . chemical engineering is a dynamic profession. It is constantly changing . . . chemical engineering education must change too or it will become irrelevant and die.

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Charles A. Sleicher is Chair of the Department of Chemical Engineering at the University of Washington, a position he has held since 1977. He has a BS in chemistry from Brown University, and the MS and PhD degrees in chemical engineering from M. I. T. and the University of Michigan, respectively. He worked for the Shell Development Company for four years before joining the faculty of the University of Washington in 1960.

seek the same jobs. That is important. Most companies that hire BS chemical engineers do not hire them from non-accredited programs. On the other hand, most companies do not need accreditation to tell them what programs are of high quality, so this consideration is of little importance.

4. Accreditation affects the administration's view of the department and, therefore, its budget. That is, of course, important, but should be regarded as a necessary evil in the sense that Program A needs accreditation only because it might otherwise be regarded, sometimes even by the Dean, as inferior to accredited programs B, C, and D. This argument cuts both ways; in some cases an accreditation report that faults a department might result in decreased support, while in other cases threatened loss of accreditation might result in increased support to remedy deficiencies.

The sacrifices a department makes for accreditation are these:

- 1. It is a modest direct expense. The current minimum cost of accreditation is \$1025, plus \$1025 for each pro-*

**Can accreditation requirements accommodate the range of changes discussed in the Amundson report . . . ?
The answer is no. What will happen instead is that no department will wish to endanger its
accreditation, and the rigidity of the ABET requirements will severely restrict
the scope and implementation of those changes.**

gram, plus \$50-150 per year, plus other miscellaneous charges.

2. It is a large indirect expense and a gigantic headache for the department. Extensive documentation of every aspect of the department as well as supporting facilities and departments is required. Hundreds of hours of faculty and staff time go into the preparation of the required reports.

3. Many faculty members spend much time on ABET committee work or act as program evaluators. Through a sense of obligation to the profession, they sacrifice valuable time to undertake these tasks (and they deserve more credit and thanks than they usually get).

4. The fourth cost, and by far the most important, is that accreditation requirements place constraints on curricula that unduly limit creative experimentation in curriculum design and that severely limit the capacity of departments to respond to changes in the profession. Moreover, present requirements leave almost no time for electives. This cost is borne not alone by departments but by their students and the profession as well.

The remainder of this paper concerns certain negative effects of accreditation on chemical engineering curricula and what might be done to make improvements.

We all know that chemical engineering is a dynamic profession. It is constantly changing, but the rate of change, like that of evolution, is uneven. Periods of slow change are punctuated by periods of sudden change, such as the one we have gone through in the past five years. Chemical engineering education must change too or it will become irrelevant and die. Indeed, signs of change in curricula are apparent. Many departments have made, or are about to make, changes in curricula in response to recent changes in the profession, and the "Amundson Report" will certainly stimulate more.

The central theme in most of these revisions is increased flexibility—more options for the students. A thoughtful and provocative article on this theme appeared in the spring 1987 issue of *Chemical Engineering Education* by Richard Felder and entitled, "The Future Chemical Engineering Curriculum—Must One Size Fit All?" Professor Felder argues persuasively for flexibility in the curriculum. He asks why not "abandon the pretense that all of our students

have the same needs and can therefore be served by the same curriculum, give or take a few electives?" He then proposes some steps towards restructuring a chemical engineering curriculum. Neither he nor apparently anyone else, however, is proposing radical changes. The basic chemical engineering material will still be there, but there is obsolete material in our curricula that should be removed. In fact, in the same issue Phil Wankat has some suggestions as to what should be removed to make room for new material.

No two chemical engineering faculties are alike, and so if the curricula of many departments are restructured, there will inevitably be less uniformity among departments than there is now, and therein lies the rub with accreditation. Can accreditation requirements accommodate the range of changes discussed in the Amundson report now being considered by many departments? The answer is no. What will happen instead is that no department will wish to endanger its accreditation, and the rigidity of the ABET requirements will severely restrict the scope and implementation of those changes.

For many departments the principal accreditation problem centers on the ABET engineering science requirement, which is one year or thirty-two semester credits of a narrowly restrictive definition of engineering science. There are two subsets of problems here: the distinction between engineering science and basic science on one hand and between engineering science and engineering design on the other. We will look at each. First, the engineering science/basic science problem.

One of the great strengths of chemical engineering curricula is that their graduates are adaptable to a wide range of technologies and, moreover, are able relatively easily to change career directions in mid-stream. They are able to do so because they are well-grounded in basic science and fundamentals. Compared with other engineering disciplines, chemical engineering students take about the same amount of math and physics but a vastly larger amount of chemistry (typically twenty-six semester credits versus about four for other disciplines). But the heavy dose of basic science takes a big chunk out of the curriculum. In fact, basic science and engineering science together take up almost exactly two years, or one-half of the curriculum.

The reason that engineering science is a problem

lies in its ABET definition and the interpretation of that definition by evaluators. The relevant words are:

The objective of the studies in *basic science* is to acquire fundamental knowledge about nature and its phenomena, including quantitative expression. The engineering sciences have their roots in mathematics and basic science, but carry knowledge further toward creative application. These studies provide a bridge between mathematics/basic sciences and engineering practice. While it is recognized that some subject areas may be taught from the standpoint of either basic science or engineering science, the ultimate determination of engineering science content is based on the extent to which there is extension of knowledge toward creative application."

Clearly, the foregoing definition requires judgment, and opinions will differ. However, the guidelines of the Engineering and Accreditation (E&A) Committee of the AIChE state that: "Instruction in this category (*engineering science*) will ordinarily be given both by the chemical engineering faculty and the faculty of other engineering departments." Therefore, although the disclaimer "ordinarily" is in place, the *practice* of some accrediting evaluators has been to define basic science as science taught in basic science departments and engineering science as science taught in engineering departments, and *in practice* it is rare that a course taught outside of an engineering department is allowed to count as engineering science.

The E&A Committee is, of course, aware of this basic science/engineering science problem and has taken four steps to alleviate it. The first and most important step was taken some years ago when 1/5 year of advanced chemistry was allowed to count toward the engineering science requirement, *i.e.*, it could be double counted as engineering science and advanced chemistry. That simple idea was a great help to curriculum planning and flexibility.

The next step was in December 1984 when Bryce Andersen, then chair of the E&A Committee, wrote a memo to all chemical engineering department chairs on the subject, "A Possible Change in the Chemical Engineering Program Criteria." The memo said that the committee was considering a change in requirements and asked for comment. The proposed change was to allow 1/4 year of advanced science, instead of 1/5 year of advanced chemistry, to count as engineering science.

The proposed change was a step in the right direction but was too small to be significant. It meant that an additional 1-1/2 semester credits, *i.e.*, about 1/2 of a course, could be counted as engineering science. A better choice would be to permit 1/3 to 1/2 year of

advanced science to count as engineering science. There are two reasons for this suggestion. First, basic science and engineering science are sometimes difficult to distinguish. There are, of course, extremes of science and applied or engineering science, but there is also a huge range of grey in between that often makes the distinction irrelevant. Today, many courses in such disciplines as chemistry, physics, biochemistry, and even genetics, microbiology, and applied mathematics, are more applied, more engineering-oriented, than are other courses in those departments, *i.e.*, these courses contain a substantial element of engineering science. Second, chemical engineers pride themselves on their flexibility and their ability to change the direction of their careers in response to the vagaries of the job market. This flexibility can only be provided if the chemical engineer has a strong background in fundamentals. As new technologies develop, this flexibility becomes ever more important.

The change of 1/5 to 1/4 year proposed by the committee was put into practice except that only advanced chemistry, not advanced science, was allowed to count. Strong letters of support from several department chairmen urging a change to 1/3 year did not affect the committee decision.

The final two changes to increase flexibility occurred just last year. One was to combine the math and basic science requirement. Instead of 1/2 year of each, the requirement is now one year of both, provided the math includes differential equations. That is an ABET requirement applicable to all engineering disciplines. But since chemical engineering has so much basic science, the new requirement amounts to allowing a decrease in mathematics. That provides a little flexibility, but not much. Most chemical engineering departments probably will not reduce their math requirement.

Finally, the latest change in requirements allows certain courses to qualify as advanced chemistry. The wording is: "If a course deals with changes in composition, structure, and properties of matter at an advanced level, then it may qualify as an advanced chemistry course, *regardless of the department in which it is taught*" (emphasis added).

Again, that is a step in the right direction, but only a tiny one. What is needed is to replace the previously quoted and misleading sentence, "Instruction in this category. . .," by a statement that would explicitly allow a course to count toward the engineering science requirement even if taught outside of engineering. That would *really* help. E&A Committee guidelines might go something like this: "Instruction in engineer-

ing science will ordinarily be given by the faculty of an engineering department, but up to six semester credits of courses in other departments that extend basic science toward creative application may also count toward the engineering science requirement."

Now let us look at the engineering science/engineering design problem. Like the distinction between basic and engineering science, the distinction between engineering science and design is not always clear. In fact, the ABET definition of design is quite broad¹; some topics straddle the line and whether pigeonholed in one slot or the other might depend on where or how they are taught or on the judgment or prejudice of the teacher. Moreover, a new topic has appeared, *design science*. Which pigeonhole will that fit in? At present, every engineering course must be assigned x credits of engineering science and y credits of design. Then the credits for all courses are totaled and the hope is that it sums to 1.0 year for engineering science and 0.5 for design. If it does not, then the figures are juggled a little, or course substitutions are made, or a course is actually restructured until the count comes out exactly right, 1.00 and 0.50. Those minimum figures are seldom exceeded.

The E&A Committee is concerned about this problem also. In fact, there has been some discussion and writing² about discarding the rigid requirement of a half a year of design and one year of engineering science and replacing it with one and a half years of both with certain restrictions, the principal one being a requirement for "a meaningful design experience." I think that appropriate wording could be found for such a change which would be a considerable help in obtaining the sort of flexibility in our curricula that will be required to meet the challenge of new technologies. It is my understanding that this change is now under consideration by the committee.

WHAT CAN BE DONE?

Quality control of chemical engineering education, accreditation, is in the hands of the profession itself. It is a voluntary, peer-review process involving both

¹The ABET definition of design has little to do with whether instruction is "practical" or not. Rather, the essence of the definition is that instruction include design problems that are open-ended and require innovative and creative intellectual activity to arrive at one of many possible solutions. Consideration of competing constraints such as economics, safety, reliability, aesthetics, ethics, and environmental impact are inevitably and explicitly required.

²Memorandum from John W. Prados, Chairman, E&A Committee, to Chemical Engineering Department Chairmen, 26 November 1986.

academic and industrial engineers who must develop criteria that do not stifle innovation, yet provide reasonable assurance of competent graduates. If we do not do the job well, the government will do it for us, and that threat ought to provoke at least some readers to make their views known to the E&A Committee.

The members of the ABET and of the E&A Committee represent all of us. Many of their members, however, apparently think that accreditation requirements are already flexible enough. ABET Curriculum Policy #8 is:

To avoid rigid standards as a basis for accreditation in order to prevent standardization or ossification of engineering education, and to encourage well-planned experimentation.

The E&A Committee has a similar statement. The job for those of us in the trenches is to convince ABET and the E&A Committee that in order to abide faithfully by this policy statement, they must further liberalize the curriculum requirements.

The wheels of ABET and the E&A Committee grind so slowly that any changes made might be both too little and too late. The profession will suffer as a result. Therefore, the effort should be made to influence them now. As experience has shown, letters from half a dozen chairmen have little effect. We need much more support than that. What we must do is to express our concerns vocally, in writing, and often to members of the Committee and to the AIChE Council itself. Letters can be addressed to committee members at their addresses or to them through AIChE at 345 East 47 Street, New York, 10017.

The 1988-1989 members of the AIChE E&A Committee are John W. Prados (Chairman), Robert R. Furgason (Vice Chairman), L. Bryce Andersen (Past Chairman), Dan Luss (Council Liaison), Harold I. Abramson (Staff Liaison), Donald K. Anderson*, Edward L. Cussler, John L. Hudson, Gilbert V. McGurl, Stanley I. Proctor, Herman Bieber, Charles A. Eckert, Larry A. Kaye, Francis S. Manning, T. W. Fraser Russell, Warren D. Seider, David T. Camp*, Robert A. Greenkorn*, James G. Knudsen, William H. Manogue*, Richard C. Seagrave.

ACKNOWLEDGMENT

The author acknowledges with thanks helpful discussion and correspondence with Prof. John W. Prados. □

*AIChE representative on the ABET E&A Commission.

CHEATING AMONG ENGINEERING STUDENTS

Reasons for Concern

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and

EDWIN A. SISSON
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Akron, OH

IN RECENT DECADES, our society has become increasingly dependent upon engineers. As it becomes more technologically complex, engineers will be called upon to make decisions of ever greater importance to society. Recent events, however, cast serious doubt upon the capability of some engineers to make appropriate ethical decisions in their work.

There are several recent and catastrophic examples of unethical behavior among some engineers. Included among these is the decision of Ford Motor Company to market the Pinto automobile, even though testimony indicates that at least one high-ranking engineer considered the design unsafe [1]. Another example concerns the B. F. Goodrich con-

tract to develop a 4-rotor brake. When tested, the brake failed to meet specifications, but regardless of the contradictory test data, the engineers involved were instructed to draft a positive qualification report. In order to do this, the engineers had to use falsified data. One of them consulted an attorney and was advised to inform the FBI, eventually exposing the fraud, but only after—not before—his complicity in the fraud.

A third example of unethical behavior concerns the 1974 Paris crash of a DC-10 airplane. One engineer thought that the cargo door and passenger supports should be redesigned, yet his supervisor decided against modifications for fear that their firm would have to pay for the redesign costs. Although they now know that should have been the proper course of action, they both admitted that at the time it posed “an interesting legal and moral problem.” Apparently not interesting enough.

Of course, only a small percentage of engineers engage in such behavior, and even those who do are seldom responsible for consequences as serious as those described above. Nonetheless, only a few such occurrences are enough to make us consider how to better help engineers avoid such situations.

To begin with, one might examine the extent and quality of ethics instruction received by most engineering students. Two observations are pertinent. First, one notes that there are few, if any, courses in engineering ethics offered in most engineering programs. Second, and perhaps more problematic, is the inadequate action taken by most engineering faculty and departments to prevent or respond to academic dishonesty. Academic dishonesty is a serious problem: if students learn to cheat with impunity in the classroom, they might continue to cheat when gainfully employed.

Inasmuch as cheating appears to be pervasive, on the increase, and perceived by many students as legitimate, there is need to be concerned about its impact. One study, conducted by the Arizona State University College of Engineering and Applied Sciences, found that 56% of 364 students polled had



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Edwin Sisson attended the University of Nebraska, Lincoln, and has BS degrees in chemical engineering and communication. He is currently enrolled in Case Western Reserve University's MBA program and is employed by the Goodyear Tire and Rubber Company. He has held jobs in production, development and marketing. (R)

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Despite the serious nature of the possible consequences of academic dishonesty, too few instructors implement measures for prevention, controlling, or detecting the problem. Reasons for this may be a lack of departmental or university support in prosecuting offenders, an attitude that teachers ought not act as police officers . . .

cheated [5]. Sisson and Todd-Mancillas found that 56% of the entire graduating class of engineers (287) had in one way or another cheated [6].

Instructor complacency, pressure to win, and student ignorance appear to be the main reasons why cheating is widespread and increasing. Also, some research has been done which helps us to better understand how cheaters justify their behavior [8]. Dienstbier's findings lead him to conclude that students are most likely to cheat when they feel subjected to intense and seemingly unjustified pressure. He further concludes that eventually cheaters learn to perceive their academic dishonesty not as morally unjustified or even as questionable, but rather as a necessary and rational way of coping with the pressure to get good grades. Having developed a perspective justifying and promoting academic dishonesty, it is probable that the cheater goes on to apply this self-serving perspective to a variety of other circumstances, which, like stressful academic environments, pose no assurance of success, yet great pressure to succeed.

Thus, upon graduation and finding oneself in the midst of a highly competitive work environment, an engineer (one who formerly developed the ability to rationalize academically dishonest behaviors) may cheat on the job as well. This cheating may be manifested in defrauding documents, such as those forged by B. F. Goodrich engineers discussed earlier. Just as students cheat in school as a means of coping with academic pressure, these engineers cheated as a means of coping with the professional demands of the marketplace. Regretfully, these engineers will now have to suffer the long-term psychic and financial cost of their involvement in the fraud. There is, then, reason to be concerned about the long-range consequences of cheating on cheaters themselves. But what of the consequences to other students? The non-cheating student suffers at least as much as the cheating student does. Statistically, even a small percentage of cheating students will create distorted grades, putting an honest student at severe disadvantage. Furthermore, this distortion is exacerbated in engineering courses where partial credit and curving are common grading practices. For instance, by merely glancing at another's paper, a dishonest student may learn how to set up a problem. Later, that student may claim, "At least I set up the problem correctly, and that

should be worth at least 60 percent."

While dishonesty in the classroom puts honest students at a disadvantage, at least insofar as achieving high grades is concerned, two other consequences are even more serious. First, dishonest students obtain an unfair advantage when seeking employment, as employers prefer to hire applicants with better academic records. Second, the dishonest student has an unfair advantage when applying for scholarships and admission to graduate school.

Presume, for instance, that a company hires an engineering graduate of University X who had dishonestly obtained a high G.P.A. Subsequently, the company discovers that the engineer's job performance is far below what had been anticipated, given the engineer's impressive undergraduate record. In the future, that company may be less likely to rely on the academic records of other students graduating from University X, or perhaps the company's experience with this particular engineer will be so disappointing that they will recruit from other universities in the future. A similar predicament may occur when a student is admitted to graduate school on the basis of a dishonestly obtained (inflated) G.P.A. Conceivably, the student might be unable to perform at the level of competence expected of him, resulting in failure to complete the program. Disappointment in this student's performance may cause this graduate program to exercise greater caution when selecting future applicants from University X. This would be unfair to future applicants whose competencies may be very real, but whose grade point averages are lower than the one obtained dishonestly by the previously admitted student.

Despite the serious nature of the possible consequences of academic dishonesty, too few instructors implement measures for prevention, controlling, or detecting the problem. Reasons for this may be a lack of departmental or university support in prosecuting offenders, an attitude that teachers ought not act as police officers, a disregard for either the high frequency of cheating or its serious short- and long-term consequences, or simple ignorance of how to prevent and control cheating in engineering courses. Some of the reasons listed above seem to account for inaction, and it was for this reason that a detailed consideration of the consequences of cheating has been presented in

Continued on page 56.

A COURSE TO EXAMINE CONTEMPORARY THERMODYNAMICS*

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“OUR VISION OF nature is undergoing a radical change toward the multiple, the temporal, and the complex.” These are the opening words of the preface to *Order Out of Chaos* by Ilya Prigogine and Isabelle Stengers [1]. Many instructors of engineering thermodynamics would probably agree that there is little evidence of anything “radical” going on in regards to the content of the typical undergraduate courses in thermodynamics. Engineers are taught basic thermodynamic principles with which they can eventually enter the world of industry and enjoy meaningful technical careers. These principles as pre-



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sented in the various textbooks on the subject have undergone little change in the recent past. This in itself is not necessarily bad, for many have recognized that this thermodynamic “toolkit” with which we are equipping our students (or, as H. G. Jones calls them, “thermodynamic plumbers” [2]) is really a powerful collection of ideas and methodologies. Keeping within the narrow confines of chemical or mechanical engineering, students often fail to realize just how powerful their thermodynamic “toolkits” can be. For example, anyone who is aware of recent developments

TABLE 1
Course Outline

- I. An introduction to philosophy of science
 - A. Logic, reasoning processes, and logical fallacies
 - B. Scientific method
 - Inductivism
 - Falsification
 - Other methods
 - C. Theories, hypotheses, *etc.*
- II. Entropy and its many forms
 - A. The second law and its historical and scientific basis
 - B. Forms of entropy
 - "Steam engine" entropy
 - Statistical entropy
 - Informational (Shannon) entropy
 - Others (*e.g.*, "negentropy")
 - C. Irreversibility and its implications
- III. Contemporary thermodynamic concepts and related topics
 - A. Time and time's arrows
 - B. "Brussels school" concepts and theories
 - C. Bifurcation and catastrophe theory
 - D. Cybernetics, synergetics, systems theory, and related theories
 - E. Fractals
 - F. Non-Western viewpoints
- IV. Thermodynamic analysis in other disciplines
 - A. Biology
 - First law: Does it apply?
 - Second law: Does it apply?
 - B. Psychology, social sciences, *etc.*

. . . there have been many exciting developments in such diverse fields as psychiatry, biology, and social science. Thermodynamicists are providing new insights into these fields—fields which many scientists previously thought were not amenable to thermodynamic “intrusions.”

in the application of thermodynamic concepts knows that there have been many exciting developments in such diverse fields as psychiatry, biology, and social science. Thermodynamicists are providing new insights into these fields—fields which many scientists previously thought were not amenable to thermodynamic “intrusions.” Most engineering students are unaware of this. They think thermodynamics is something confined to heat engines and not much more.

Even when the discussion is confined to more technical matters of physical science, students are often unaware of the recent advances in thermodynamics. Most of them leave with their Bachelor of Science degrees, never having heard of such things as “dissipative structures” and having received only limited exposure to the general field of irreversible thermodynamics. “Catastrophies” may be associated more with test performance rather than with a powerful analytical tool. In many ways, their knowledge of thermodynamics may be more reflective of the closed system close-to-equilibrium mentality of the past.

Finally, their understanding of very basic concepts such as entropy and the second law is often poor. As one person lamented, “One of the most highly developed skills in contemporary Western civilization is dissection: the split-up of problems into their smallest possible components . . . we often forget to put the pieces back together again” (A. Toffler in [1]). Indeed, many professors have noted that engineering students probably work harder than other students, but may not possess sufficient critical analytical skills or *philosophical* abilities. This is not all that surprising, given the pragmatic or empirical nature of engineering “science.” We teach students how to work problems, often resorting to “black box” strategies, but rarely do they get to sit back and just “think,” particularly in a more qualitative philosophical sense.

With these things in mind, we developed a course which would give students a chance to critically think about and otherwise analyze the contents of their thermodynamic “toolkits.” In addition, the students would be exposed to recent developments in thermodynamics and related topics, including attempted applications to fields other than the physical sciences. Finally, students were exposed to the general field of philosophy of science in an attempt to stimulate further development of their critical skills.

COURSE OBJECTIVES AND OUTLINE

The course was organized to achieve four broad objectives:

- To critically discuss and analyze fundamental thermodynamic concepts such as entropy
- To expose the student to contemporary thermodynamic concepts such as those put forth by the “Brussels group” and to related topics such as bifurcation theory
- To critically discuss attempted applications of the above objectives to other fields, particularly to the life sciences
- To introduce the student to the field of philosophy of science, including logic and scientific method.

Table 1 presents the course outline. The course was run in a seminar fashion to encourage student discussions. During the first offering of the course, the books presented in Table 2 were utilized, and

TABLE 2
Books Utilized in the Course

Required Texts

- *Time's Arrows*, by R. Morris; Simon & Schuster, New York, 1985
- *Order Out of Chaos*, by I. Prigogine, I. Stengers; Bantam Books, Toronto, 1984
- *The Systems View of the World*, by E. Laszlo; George Braziller Inc., New York, 1972
- *An Introduction to Catastrophe Theory*, by P. T. Saunders; Cambridge University Press, New York, 1980

Referenced Texts (Texts which were referred to repeatedly during the course.)

- *The Tao of Physics*, by F. Capra; Shambhala, Berkeley, 1975
 - *Entropy*, by J. D. Fast; Gordon & Breach, New York, 1968
 - *Against Method*, by P. Feyerabend; Thetford Press Limited, Thetford, 1978
 - *The Structure of Scientific Revolutions*, by T. S. Kuhn; University of Chicago Press, Chicago, 1970
 - *Conjectures and Refutations: The Growth of Scientific Knowledge*, by K. R. Popper; Harper & Row Publishers, Inc., New York, 1965
 - *Entropy: A New World View*, by J. Rifkin; Viking Press, New York, 1980
 - *The Tragicomical History of Thermodynamics 1822-1854*, by C. Turesdell; Springer-Verlag, New York, 1980
 - *Catastrophe Theory*, by A. Woodcock, M. Davis; E. P. Dutton, New York, 1978
-

numerous journal articles were discussed. A list of the more useful journal articles is presented in Table 3. While the course was basically run by myself, I found that the presentation of scientific method by an actual philosopher of science to be particularly effective.

The typical assignment was to read the assigned materials and be prepared to discuss them but there were also several assignments which required some library work. For example, students were instructed to find specific examples of the application of catastrophe theory and present them to the class. Overall grading was based on a consideration of in-class participation (reflecting preparation), the written assignments, and performance on a comprehensive final exam.

DISCUSSION

On the first day, I gave a simple quiz that consisted of two parts: 1) define the words *entropy*, *time*, *order*, and *stability*; 2) define *hypothesis*, *law*, and *theory*, and outline how you would prove a given hypothesis. The answers to the first part were rather poor. In fact, blanks appeared with an alarming frequency. Answers to the second part were typically inductive in nature—"go run experiments." Following the quiz, students readily admitted their personal embarrassment over their performances. But while a few egos may have been bruised, students for the most part had a clearer understanding of the importance of the class objectives. A point had been made.

Further in-class discussion on the nature of entropy revealed the usual associations with *order* and *chaos*. Others have written on this superficial understanding as expressed by "naive" students (for example, see [3]). All students challenged the idea that movement further and further away from equilibrium could possibly lead to the creation of stable structures. Again, it was clear that the students' basic understanding of the thermodynamic fundamentals was narrow and shallow.

The typical class consisted of some initial lecturing, usually outlining the basic ideas associated with the assigned readings and sometimes presenting historical perspectives. Most of the class time was devoted to free-style discussions. A key to this sort of format is to maintain several opinions for a while and not to converge on a "right" answer (if there even is one) too quickly. In fact, sometimes there may be several tenable explanations (for example, what is time?) and the students are left to make up their own minds.

I found it was a good strategy to present the

TABLE 3
Selected Journal Articles Utilized in the Course

- "Equilibrium, Entropy, and Homeostasis: A Multidisciplinary Legacy," by K. D. Baily; *Systems Res.* 1, 1984; 25-43
 - "The Theory of Open Systems in Physics and Biology," by L. von Bertalanffy; *Science*, III, 1950; 23-29
 - "Life, Thermodynamics, and Cybernetics," by L. Brillouin; *Am. Scientist*, 37, 1949; 554-568
 - "Entropy and Disorder," by J. M. Burgers; *Brit. J. Phil. Sci.*, 5, 1954; 70-71
 - "The Interdisciplinary Study of Time," by J. T. Fraser; *Ann. NY Acad. Sci.*, 138 (art. 2), 1967; 822-847
 - "Entropic Models in Biology: The Next Scientific Revolution?" by D. P. Jones; *Persp. Biol. Med.*, 20, 1977; 285-299
 - "Order and Irreversibility," by P. Kroes; *Nature and System*, 4, 1982; 115-129
 - "Gibbs vs. Shannon Entropies," by R. L. Liboff; *J. Stat. Phys.*, 11, 1974; 343-357
 - "Maxwell Demon and the Correspondence Between Information and Entropy," by R. P. Poplavskii; *Sov. Phys. Usp.*, 22, 1979; 371-380
 - "Time's Arrow and Entropy," by K. Popper; *Nature*, 207, 1965; 233-234
 - "Can Thermodynamics Explain Biological Order?" by I. Prigogine; *Impact Sci. Soc.*, 23, 1973; 151-179
 - "Should Irreversible Thermodynamics be Applied to Metabolic Systems?" discussion forum; *Trends Biochem. Sci.*, 7, 1982; 275-279
 - "Entropy, Not Negentropy," by J. A. Wilson; *Nature*, 219, 1968; 535-536
-

philosophy of science topics first. It provided a framework for later critical discussions. Questions such as, "Is it a testable hypothesis?" or, "What logical fallacy is being committed?" could be posed more intelligently. The main scientific method lecture was presented by a philosopher of science. This proved to be a good move since it gave the students a chance to see that philosophers might actually have something of value to offer engineering students. Also, students found the discussion on various scientific methods (*e.g.*, inductivism, falsification, *etc.*) to be very stimulating.

I also tried to present conflicting views whenever appropriate. The article "Gibbs vs. Shannon Entropies" (see Table 3) is an example of this. The forum-style article "Should Irreversible Thermodynamics be Applied to Metabolic Systems?" (see Table 3) is another example. In general, a fair presentation of the strong points *and* the weak points of a given viewpoint should always be made.

The books *Time's Arrows* and *Order Out of Chaos* were excellent choices. I currently plan to use the book *What is This Thing Called Science* [4] as the third principle text the next time the course is offered. It is a good overview of recent topics in scientific method. However, there are probably other available

books that could also serve this purpose. The remaining topics in Table 1 can be handled with lecture notes and relevant journal articles.

I judged this course to be effective based on several observations. First, the same quiz previously given on the first day was also given near the end of the class, and needless to say, the answers were much more satisfactory. In fact, students felt they did not have enough time to respond completely. Second, the students themselves seemed to feel more confident of their understanding of thermodynamics. While there may have been periods of confusion (probably a good sign) during the semester, students generally emerged on a firmer basis. Finally, several students stated that they planned to continue their self-education in the topics they were exposed to during the course.

ACKNOWLEDGEMENTS

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DISCUSSION: The reviewers of this paper presented some interesting comments of their own. We feel their views deserve consideration and present them here for our readers' information

Review #1:

Although I have serious reservations about the course described by Lee, I am not inclined to recommend rejection of his manuscript. Thus, while I may deplore his poor taste (...applications of thermodynamics to problems in psychiatry and social science? Why not throw in psychohistory and social Darwinism as well? and... [exposure to] philosophy of science in an attempt to stimulate...critical skills. He apparently has had much better experiences with philosophers of science than I), he has taught the course and so does have something to report.

If there is a single "fault" to the plan, it is Lee's strategy of bolstering students' admittedly inadequate understanding of a well-defined subject (thermodynamics) by exposing them to ideas about other topics, namely, the philosophy of science (a discipline that is itself disdained by many knowledgeable scientists and scientific historians for whom I have great respect), Prigogine's dissipative structures stuff, and the pseudo-scientific applications of thermodynamic terminology to psychiatry and social science. That last one really gets me. These are interesting items, perfectly suitable for dinner table conversation, but unlikely to advance the understanding of thermodynamics. Still, I doubt that it can hurt...and it is comforting to see that the "simple quiz"...doesn't include the Mumbo Jumbo. If the course enhances the students' understanding of these terms and concepts, then it probably is worthwhile. I would opt for more attention to these and less for the topics about which I already have vented my spleen. Finally, a course that attempts to cover so many complex topics surely must be superficial: how do students discuss whether

irreversible thermodynamics should be applied to metabolic systems...without a thorough grounding in irreversible thermodynamics?

In summary, I recommend that the manuscript be published so that others can judge for themselves whether this or a related course should be included in their own curricula.

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Review #2:

I agree with the author that many undergraduates do not develop a good understanding of thermodynamics, especially of the Second Law. There are several reasons for this, including hasty exposure and emphasis on routine and mechanized problem solving, overloading with other courses, etc. The cure, in my opinion, is emphasis on critical understanding, more interesting problems and more substantial injection of statistical thermodynamics.

As for irreversible thermodynamics of the Prigogine fame, this reviewer believes that the subject is practically useless to chemical engineering. The only contribution that irreversible thermodynamics has made to our discipline stems from the Onsager relations which provide a framework for constitutive transport relations. Applications to social sciences or medicine are best tackled by more experienced workers and not by the undergraduates who struggle with basic physics and chemistry.

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DESIGN EDUCATION IN CHEMICAL ENGINEERING

PART 1: Deriving Conceptual Design Tools

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MOST OF THE CHEMICAL engineering curriculum is focused on the analysis of either engineering science problems or single unit operations. That is, very well-defined physical systems that normally involve chemical (or biological) reactions and/or separations, are investigated in considerable detail. Students usually do not encounter any synthesis problems until their senior year design course, where one of the goals is to integrate the complete curriculum by demonstrating how the individual process units fit together into a large system, *i.e.*, a chemical process. However, because of time constraints, usually only a narrow range of design problems is considered.

The purpose of this paper is to describe the spectrum of process design problems and to suggest a methodology for teaching the important concepts used in design. The topics that will be considered are: the types of processes considered and their designs, some new tools that are useful in conceptual design, and a strategy for developing conceptual designs.

CLASSIFICATION OF PROCESSES

We can classify processes in a variety of ways, including the type of operation, what they produce, and the types of products they make. There are two main types of operations: continuous and batch. Continuous processes are designed to operate twenty-four hours a day, seven days a week, for 300 to 350 days a year, and hopefully, nothing changes with time. In contrast, batch plants contain units that are deliberately started and stopped according to some schedule. They may operate twenty-four hours a day, or they might be designed to operate for only a single shift.

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Batch plants are more flexible, but they are usually less efficient than continuous processes. In general, continuous processes are associated with large production capacities, whereas batch plants are associated with specialty chemicals.

Another way of classifying processes depends on the number of products they produce. Some plants produce only a single product stream, whereas others might produce several products simultaneously. Still others might produce different products in the same equipment, but at different times of the year.

We can further define a process based on the characteristics of the product. Sometimes we may wish to produce pure chemical compounds (petrochemical processes), while at other times the final product is a mixture (there are hundreds of com-



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Experience indicates that less than 1% of the ideas for new designs ever becomes commercialized. In order to avoid expensive failures, it is common practice for process engineers to develop a hierarchy of designs where the accuracy of the design calculations and the amount of detail considered increases as the next level in the hierarchy is considered.

pounds in gasoline or furnace oil streams). In still other instances we produce materials that are described by distribution functions (solid products are usually characterized by a particle size distribution, and polymer products are normally characterized as a function of their molecular weight distribution).

Since such a wide variety of processes exists, it is not surprising that different design techniques and criteria are applicable. Moreover, it should be apparent that there is not enough time in an undergraduate's program to discuss all of these types of problems. Thus, it has been common practice to have undergraduates consider the design of only one type process (usually a petrochemical process that produces a single, pure product) in the design course.

A GENERAL STRATEGY FOR APPROACHING DESIGN PROBLEMS

Experience indicates that less than 1% of the ideas for new designs ever becomes commercialized. In order to avoid expensive failures, it is common practice for process engineers to develop a hierarchy of designs where the accuracy of the design calculations and the amount of detail considered increases as the next level in the hierarchy is considered (see Table 1, from [2]). The design course in chemical engineering looks at Level 2 for a single process. That is, the students are given a flowsheet, *i.e.*, a description of the process units and the interconnections between these units. They calculate the process material and energy balances, the required equipment sizes, the utility flows, the capital and operating costs, and the process profitability. The design calculation routines used are fairly rigorous so that obtaining a solution normally requires extensive iteration, which often becomes quite tedious.

Most design research has focused on Levels 2 and 3 in the hierarchy. The emphasis has been on the development of improved algorithms for the rigorous design of a variety of types of equipment or complete flowsheets. Similarly, improved optimization procedures for various types of problems have received considerable attention.

Level 1 in the hierarchy of Table 1, also known as the conceptual design phase, is usually undertaken by experienced engineers. They use numerous heuristics and back-of-the-envelope calculations to develop the

TABLE 1
Types of Designs

1. Order of magnitude estimate (*Error about 40%*)
2. Factored estimate (*Error about 25%*)
3. Budget authorization estimate (*Error about 12%*)
4. Project control estimate (*Error about 6%*)
5. Contractor's estimate (*Error about 3%*)

first design, *i.e.*, the base-case design, and then to screen the process alternatives. In some companies an engineer is sent to a chemist's laboratory as soon as the chemist has discovered a new reaction or a new catalyst, and the engineer is expected to complete a base-case design within a period of two days to one week. The results of this design study are then used to help guide the development of the project.

TEACHING CONCEPTUAL DESIGN

Conceptual design is a creative activity where the goal is to find the best flowsheet from a large number of process alternatives. If one were to blindly consider all of the possible alternatives, it would be necessary to consider something like 10^4 to 10^9 flowsheets. According to Westerberg [4], each flowsheet is described by about 10,000 to 20,000 equations, and there are usually ten to twenty optimization variables associated with each alternative. It is necessary to compare these alternatives at close to the optimum design conditions in order to determine the best flowsheet. Typical of design problems in other disciplines, chemical process design problems are characterized by the combinatorially explosive nature of the possible solutions.

The question then arises as to whether it is possible to teach undergraduates how to complete a first design in a two-day to one-week period, and how to determine the best flowsheet in another two-day to one-week time frame. This requirement implies that it will be necessary to teach them how to derive back-of-the-envelope calculation procedures and how to derive heuristics, since these are the tools used by experienced engineers. It will also be necessary to teach the undergraduates a systems approach to synthesis which emphasizes the interactions that may occur when we put a complete process together. A discussion of some new tools of this type follows.

DERIVING BACK-OF-THE-ENVELOPE DESIGN MODELS

Chemical engineers are used to having a hierarchy of models, with increasing orders of complexity and accuracy, available for solving various problems. For example, the Navier-Stokes equations used in fluid mechanics are sufficiently complex that it is necessary to use order-of-magnitude (or scaling) arguments to simplify them in order to obtain an answer. It is surprising that no one seems to have attempted to use this same approach to simplify models in other problem areas, such as equipment or process design.

One could use order-of-magnitude arguments to derive a back-of-the-envelope model for an isothermal, plate-type gas absorber used to recover solutes from a dilute feed stream. For this special class of absorber problems there is an analytical solution, called the Kremser equation [1], which most undergraduates have studied.

$$N + 1 = \frac{\ln \left\{ \left[\frac{L}{mG} - 1 \right] \left[\frac{Y_{in} - mX_{in}}{Y_{out} - mX_{in}} \right] + 1 \right\}}{\ln \left[\frac{L}{mG} \right]} \quad (1)$$

We would like to develop a short-form of this equation to further simplify our analysis. Since we do not need great accuracy for conceptual design (see Level 1 in Table 1) our criterion will be to drop any term that does not affect the answer by more than 10%.

We first note that most gas absorbers encountered in practice contain 10 to 20 trays, and therefore we are interested in obtaining accurate solutions when N is of the order of 10 to 20. When we examine Eq. (1) we see that order-of-magnitude arguments yield

$$N + 1 = N \quad (2)$$

For gas absorbers with pure solvent streams, $X_{in} = 0$. From other arguments it can be shown that $L/mG = 1.4$, approximately, and that $Y_{in}/Y_{out} = 100$, or so. When we compare the orders-of-magnitude of the terms in the numerator on the right-hand-side of Eq. (1), we see that

$$\ln \left\{ \left[\frac{L}{mG} - 1 \right] \left[\frac{Y_{in}}{Y_{out}} \right] + 1 \right\} = \ln \left[\frac{L}{mG} - 1 \right] \left[\frac{Y_{in}}{Y_{out}} \right] \quad (3)$$

Since $L/mG = 1.4$, we could replace the denominator in Eq. (1) by its Taylor series expansion and write, approximately

$$\ln \left[\frac{L}{mG} \right] = \left[\frac{L}{mG} - 1 \right] = 0.4 \quad (4)$$

Our result becomes, after replacing \ln by \log

$$N = \frac{2.3 \log \left[\frac{L}{mG} - 1 \right] \left[\frac{Y_{in}}{Y_{out}} \right]}{0.4} \quad (5)$$

If we are willing to sacrifice accuracy for simplicity, the final form is

$$N + 2 = 6 \log \frac{Y_{in}}{Y_{out}} \quad (6)$$

and we have achieved our goal of developing a back-of-the-envelope model.

Of course, it is essential to check our simple model against the more rigorous expression. For the case of 99% recoveries, where $Y_{in}/Y_{out} = 100$, Eq. (6) predicts 10 trays versus the rigorous value of 10.1, and for 99.9% recoveries where $Y_{in}/Y_{out} = 1000$, Eq. (6) gives $N = 16$ versus the correct value of 16.6. We have used this same procedure to develop short-cut models for process material and energy balances, a variety of equipment design procedures, cost expressions, etc.

DERIVING ERROR BOUNDS FOR DESIGN MODELS

The simple models used to describe process units or other physical relationships normally have specific limitations (*i.e.*, the Kremser equation is valid for isothermal, dilute systems and the ideal gas law is valid only for low molecular weight, non-polar materials at low pressure). Of course, students need to know when they can use these simplified models and it is easy to quantify when these approximations are valid simply by applying Taylor series expansions. For example, in order to assess the validity of the assumption of dilute, isothermal operation in a plate-type gas absorber, we can use Taylor series expansions around the condition of infinite dilution, along with some back-of-the-envelope approximations (*i.e.*, that high recoveries are equivalent to complete recovery) to show that the value of the distribution coefficient will change by less than 10% if

$$Y_{in} \left(1 + \left\{ 2(A_{21} - 2A_{12}) + \frac{\Delta H_v^2}{RC_p T_L^2} \right\} \right) < 0.1 \quad (7)$$

Thus, the dilute, isothermal assumption depends on the heat of vaporization of the solvent, as well as the inlet solute composition. We can develop a similar expression for how this assumption affects the number of plates required in the absorber by considering how

changes in m affect N in Eq. (1). This approach is simple to teach, and it provides a way of making decisions that can be used instead of experience.

DERIVING DESIGN HEURISTICS

Design heuristics were originally proposed by experienced engineers who solved similar problems many times, and then noticed common features of the solution. At the present time, however, they are being developed by graduate students who solve hundreds of case studies on a computer and then attempt to generalize the results (see Tedder and Rudd [3]). The fact that heuristics exist implies that their solutions must be insensitive to almost all of the design and cost parameters. Therefore, by eliminating these insensitive terms using order-of-magnitude arguments, it should be possible to derive heuristics.

As an example of a derivation of a heuristic, we again look at the design of the simple gas absorber problem that we considered above. The number of trays selected for the gas absorber depends on an economic trade-off, *i.e.*, as we increase the number of trays we increase the cost of the absorber, but we decrease the amount (and therefore the value) of the material that is not recovered. If we express the capital cost of the absorber on an annualized basis and assume that the total cost depends only on the number of trays and the annual value of the lost solute, we obtain

$$TAC = (C_s)(G)(Y_{in}) \left(\frac{Y_{out}}{Y_{in}} \right) (8150 \text{ hr/yr}) + (C_N)(N) \quad (8)$$

Now if we substitute Eq. (6) for N and find the optimum value of Y_{out}/Y_{in} , we obtain

$$\frac{Y_{out}}{Y_{in}} = \frac{(6)(C_N)}{(C_s)(G)(Y_{in})(8150 \text{ hr/yr})} \quad (9)$$

and by substituting some reasonable values for the parameters, we find

$$\frac{Y_{out}}{Y_{in}} = \frac{(6)(850)}{(15.4)(10)(8150)} = 0.004 \quad (10)$$

The important feature of this result is not the expression for the optimum, but the insensitivity of the solution. We note that if we make a 100% change in any of the values in either the numerator or denominator, the answer changes only from 0.002 to

0.008, which corresponds to fractional recoveries in the range from 99.2% to 99.8%. This is the basis for the well known heuristic:

It is desirable to recover more than 99% of all valuable materials.

With this simple procedure we have been able to derive most of the current heuristics used in process design, and have also been able to discover new heuristics for other design problems. Again, since we derive our heuristics, the assumptions made in the derivations will help to indicate the limitations of their applicability.

CONCLUSIONS

With the new techniques described above, the engineer now has the tools available to quickly evaluate flowsheet alternatives. In Part II of this article [which will be published in the next issue of *CEE*] we will describe how these tools, along with a hierarchical decomposition procedure to generate flowsheet alternatives, are used in a systems approach to conceptual design.

NOMENCLATURE

- A_{ij} = Margules constants of the solute and solvent at infinite dilution
- C_N = annualized absorber cost per plate, \$/plate
- C_p = heat capacity, Btu/mol-F
- C_s = value of solute, \$/mol
- G = carrier gas flowrate, mol/hr
- ΔH_v = heat of vaporization of solute, Btu/mol
- L = solvent flowrate, mol/hr
- m = slope of equilibrium line
- N = number of theoretical plates
- R = ideal gas constant, Btu/mol-F
- TAC = total annualized cost, \$/yr
- T_L = solvent temperature, deg. F.
- X = mole fraction of solute in liquid
- Y = mole fraction of solute in gas

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Random Thoughts . . .

NOBODY ASKED ME, BUT . . .

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It will probably come as a shock to those who know me, but I have some strong opinions about educational matters. Very strong. Violent and unswerving prejudices, some would say. And since I will regularly be using this forum to subject you to whatever is on my mind, I thought it would be only fair to run through these opinions for you. You may then feel free to dismiss things I say in future columns on the grounds of my admitted bias. (However, anything I say about a topic not on the list may be considered absolute truth.)

Ready? Here goes, beginning with the most violent and unswerving prejudice of them all.

- *I hate 7:50 classes.*
- *I don't like people knocking on my door when I'm doing something I really want to do. I welcome them joyfully, however, when I'm doing something I really don't want to do, like grading papers or critiquing an incomprehensible thesis draft.*
- *People who assume that all engineers are culturally ignorant, anti-environment, good at math and science but little else, boring, etc., are irritating. On the other hand, our increasingly specialized and elective-free engineering curriculum almost seems designed to assure that those stereotypes are valid.*
- *I like summers that begin in early May and end in late August (until it's late August).*
- *There is no excuse for undergraduate textbooks written for professors rather than students.*
- *I value the autonomy that comes with this job—being able to choose my research problems, work late and sleep late, stay at home occasionally on days I don't teach. I can't think of another lawful profession that provides its practitioners with so much personal freedom.*
- *I don't like stress tensors.*

- *The classroom occurrence that may be most conducive to learning is spontaneous humor. (I've been using some of the same spontaneous jokes for years.)*
- *I am bemused by students who walk into my office, see me talking on the telephone with papers and open books scattered all over my desk and another student sitting across from me, and ask (all together now), "Are you busy?"*
- *The term "real world" can be intensely annoying, especially coming from people who think they live in it and I don't.*
- *Cheating is repugnant. Even more so is the system that hangs students' futures on the grades they get on timed tests.*
- *I like anything written by Octave Levenspiel.*
- *I hate walking down two flights of stairs to the department office and then forgetting what I wanted there. (This happens with increasing frequency—I don't want to think about what that might mean.)*
- *Our second-worst assumption as teachers is that if we don't cover something in class the students won't learn it. Our worst assumption is that if we do, they will.*
- *I like word processing, spreadsheeting, computer graphics, etc., but I'm worried about how dependent I've become on the computer. At this point if it goes down, I go right down with it.*
- *I don't like anything about the PhD qualifiers—making them up, grading them, and especially discussing them at faculty meetings.*
- *It is not pleasant to discover that I really don't under-*

Richard M. Felder is a professor of ChE at N.C. State, where he has been since 1969. He received his BChE at City College of C.U.N.Y. and his PhD from Princeton. He has worked at the A.E.R.E., Harwell, and Brookhaven National Laboratory, and has presented courses on chemical engineering principles, reactor design, process optimization, and radioisotope applications to various American and foreign industries and institutions. He is coauthor of the text *Elementary Principles of Chemical Processes* (Wiley, 1986).



stand something I've been teaching for years.

- *One of our best fringe benefits is getting to give seminars in some of the world's most attractive places. (Getting honoraria for them is not a bad deal either.)*
- *There is little value and much harm in tests on which the average is in the low 30's. I'm bothered by instructors who would never admit or even consider the possibility that such tests may have been unfair or the students may have been poorly taught.*
- *A university administrator who says he won't do something can be upsetting. One who consistently says he will and then doesn't (or who is incapable of giving a straight answer) can be disastrous.*
- *I get terminally grumpy at badly delivered departmental seminars on subjects I'm not the least bit interested in.*
- *I like engineering professors with interests and talents outside of engineering. If I have a hero in our profession, it is Bob Bird.*
- *Few chores are as taxing as maintaining energy in a class that acts like a wax museum.*
- *One that is as taxing is serving on a university committee that has no real function and never accomplishes anything yet religiously meets every two weeks for at least two hours.*

I am filled with admiration for Professor Vincent M. Foote of the N.C.S.U. School of Design [may his tribe increase], who chaired a committee I served on last year. Vince called meetings only when there was something to do started the meetings on time, had us do what was needed, and adjourned. The average duration of the meetings was about 20 minutes. It was a revolutionary experience.

- *The most troublesome aspect of American engineering education is the way it penalizes outstanding teachers doing minimal research and rewards outstanding researchers doing lousy teaching.*
- *The most puzzling aspect of American engineering education is the notion that engineers with years of industrial experience but few research publications don't belong on engineering faculties.*
- *The hardest thing I have to do as a teacher is decide whether I should push the final grade of a borderline student up (providing encouragement and a challenge to live up to my high opinion) or down (maintaining high standards and providing an incentive to work harder next time).*

I envy professors who believe in their hearts that this is not a dilemma—that one of these choices is the correct one for all students on all occasions. I think they're

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dead wrong, but their lives are a lot easier than mine at least twice a year.

- *I like teaching and writing. I love having a job that pays me to do both.*

Help me out—what else should be on the list? The best entry wins a free drink at the next Exxon Suite.

AN ALTERNATE APPROACH TO THE UNDERGRADUATE THESIS

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The chemical engineering department at the Technical University of Nova Scotia (TUNS) has recently undertaken an approach to the senior undergraduate thesis which is different from the more traditional route. In the 1986-87 academic year, most of the thesis projects involved the design, construction, and testing of a piece of equipment for the undergraduate laboratory. In previous years, each student had selected a topic which was based on a professor's area of expertise and research.

Our method of organizing and handling the projects is described here, and the benefits and disadvantages of conducting undergraduate theses in this manner are discussed. We have concentrated more on the educa-



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Mort Fels received his BEng from McGill University and his PhD from the University of Waterloo. He has been teaching chemical engineering for sixteen years and is currently a professor in the chemical engineering department at the Technical University of Nova Scotia. His research interests are biomedics (artificial kidney), energy conversion, and computer-aided design. (R)

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TABLE 1
Staged Progression of Thesis Work

First Term

1. Topic Selection
2. Functional and conceptual design
3. Dimensional design
4. Framework and support structure requirements
5. Order list for components
6. Mid-term oral presentation
7. End-of-term oral presentation and written report

Second Term

1. Control panel dimensions and layout
 2. Beginning and end of construction
 3. Beginning and end of testing
 4. Mid-term oral presentation
 5. Final oral presentation and written report
-

tional aspects of our approach than on the projects themselves.

ORGANIZATION

The chemical engineering department at TUNS is relatively small, with a typical total enrollment of forty to fifty undergraduates in the three years. In 1986-87, our senior class consisted of twelve students. The students worked singly on a project which was conducted under the supervision of a professor (or professors) in the department. One faculty member also served as overall coordinator. As well as being an additional resource person for the students, he reviewed the final designs before components were ordered and also gave lectures on topics such as project management, instrumentation selection, and the design process.

A graduate student was assigned to the course as a teaching assistant. The student was selected for his practical knowledge of piping, electrical, and construction techniques and, as such, was invaluable as a resource person for the students. He also coordinated the purchase orders from the twelve projects.

An important aspect of the course structure was a schedule of events which the class was expected to

follow. Deadlines were established for the items shown in Table 1.

PROJECTS

The twelve topics offered were categorized as shown in Table 2. The three research-type projects all have potential for use in the undergraduate laboratory.

BENEFITS

The most obvious benefit from this work has been the addition of new experiments and the subsequent deletion of outdated equipment. This has resulted in a general strengthening of the undergraduate lab, particularly in the unit operations area. For example, we have replaced a large plate heat exchanger with a smaller, more versatile unit.

We have also been able to increase the use of computers in the lab, primarily in the areas of

- Data acquisition (drying)
- Data acquisition and control (single and multi-variable control experiments)
- Data reduction (plate heat exchanger)

There is no doubt that the work described here has held significant advantages for the department; but what about the students? Judging from their reaction to the work (and the quality of the finished products), they have also benefited from the experience. Student development was fostered by several factors:

- Familiarization with aspects of design and project management
- Knowledge of instrumentation
- Hands-on, practical experience
- Interaction with technicians, salesmen, etc.
- Sense of pride in the work; enhancement of class spirit
- Exposure to state-of-the-art equipment (e.g., Laser Doppler Velocimetry in the freeboard particle measurements)

Apart from the technical aspects listed above, each student was required to give four oral presentations during the course of the year, as well as two written reports (Table 1). In all cases, a noticeable improvement in communication skills occurred; with three students the improvement was almost unbelievable.

PROBLEMS

An undertaking of this nature has its inevitable drawbacks. Although, overall, the experience was con-

The most obvious benefit from this work has been the addition of new experiments and the subsequent deletion of outdated equipment. This has resulted in a general strengthening of the undergraduate lab, particularly in the unit operations area.

TABLE 2
Thesis Projects

New Experiments for Undergraduate Lab

1. Air Conditioning
2. Drying
3. Ion Exchange
4. Wetted-Wall Gas Absorption
5. Fluidized Bed Heat Transfer
6. Plate Heat Exchanger
7. Single Variable Control (Temperature)
8. Multi-Variable Control (Temperature and Level)

Upgraded Experiment for Undergraduate Lab

9. Packed Column Gas Absorption

Work on Research Projects

10. R-Value Measurement of Building Materials
11. Particle Velocity Measurements in the Freeboard of a Cold Fluidized Bed
12. Computer Control of a Coal Processing Mini Plant

sidered a success, several problems arose which are described below.

Cost

Laboratory equipment is expensive, especially if one wants to incorporate the latest advances in technology. There is a big difference in measuring temperature with a thermometer and using thermocouples with associated A/D conversion and computer data-logging. We chose, in general, a middle ground, and installed primary transducers with digital read-outs which would allow eventual upgrading to computer data-logging and control.

Total costs for each project varied from about \$500 to \$3,000. However, the alternative of purchasing off-the-shelf units (if possible) would have been many times more expensive. Some funds should be set aside to purchase those forgotten or emergency items which are always necessary at the end of the project or during initial testing.

Time

Time plays a major role in this type of thesis approach. The students, faculty and support staff devoted many hours to the work. Normally, three hours

per week for twenty-six weeks is scheduled (78 hours). It is estimated that the total time that the students spent is closer to double this figure. However, the nature of these projects is such that much of the time must be spent at the end of the final term, which is, of course, when it is the most scarce. We were concerned that the students would be unable to complete the projects in the available time. This is probably the largest risk in such a venture. A high degree of success was achieved, however, with most students meeting the objectives of the work and producing a piece of laboratory equipment which worked. Shortfalls in the program occurred in testing and preparing detailed laboratory procedures. In most cases, additional work is needed in these areas so that the experiments can be used routinely in the undergraduate laboratory.

Scheduling

The time for equipment which was slated for upgrading and which was also part of a current laboratory course required careful scheduling. Fortunately, only one project (packed column gas absorption) fell into this category. We found that it was necessary to run all the laboratory course experiments on packed column gas absorption in one time block at the beginning of the first term. Once this was accomplished, the equipment was turned over to the thesis student and the upgrading proceeded without interruption.

Type of Student

The laboratory projects require that a student have a certain degree of mechanical know-how and dexterity. Since technologist time is limited, a major amount of actual construction is necessarily performed by the student. There were a few students who lacked basic skills in this area and who had no interest in learning them. The result of this situation was that the faculty member had to put in a fair amount of time doing the actual construction.

Research Aspect

One disadvantage of this type of project is that students wishing to pursue a post-graduate degree will not be exposed to some of the concepts or techniques of research. There is no doubt that development of skills in the areas of literature searches, experimental design and general research philosophy suffered. However, development of other skills relating to equipment construction, communications and general project management is also important in research.

SUGGESTIONS

In contemplating this type of project, the following important points should be considered:

- Only do as many projects for which there is adequate funding.
- The larger projects would probably be more successful with two students working together instead of only one.
- Do not have only laboratory-type projects available; research or theoretical projects should be provided for those students who have no interest in a laboratory project.
- Ensure that enough technical help is available. Machinists, plumbers, and electricians are necessary resource people.

CONCLUSIONS

An alternate approach to the undergraduate thesis has been described. This approach lies somewhere between the traditional research-oriented thesis and the work normally done in a process and plant design course. The size of our senior class has made it possible for us to offer this experience to all members of the group. In a large institution it would still be possible to adopt this scheme, but with a smaller percentage of the seniors. While a strategy of this sort is neither desirable nor feasible to implement on a continuous basis, our one attempt has brought numerous benefits to both the department and the students involved. □

REVIEW: Direct Contact Continued from page 11.

any wall resistance and low capital cost. In specialized situations these advantages certainly will lead to further commercial use of direct contact exchangers.

The book is the product of an NSF-supported workshop held at the Solar Energy Research Institute in 1985. It contains fourteen chapters written by the organizers and principal speakers. Five chapters deal with two-phase fluid systems. Three chapters treat heat transfer between particulate solids and gases. A chapter each concerns evaporation and condensation processes.

Several valuable functions are fulfilled by this book. At the most basic level it should serve to re-emphasize to the heat transfer specialists that this kind of heat exchanger is an option with certain strong advantages. The book is a good source of ideas and configurations for possible applications. A valuable feature of the book is a set of design examples included as six appendices. In the final chapter the editors present a summary of research needs. □

CHEMICAL REACTOR DESIGNby *E. B. Nauman**John Wiley & Sons., \$53.70 (1987)*

Reviewed by

P. A. Ramachandran**Washington University**

Chemical reaction engineering has evolved to a mature discipline in the last two decades, and this has resulted in a number of textbooks and monographs on the subject. The computer revolution has embraced this field in a big way, and the trend is towards detailed modeling and optimization studies of industrial scale reactors. The textbook coverage on the application of numerical methods in reaction engineering is, however, minimal and the present book fills this important gap. Thus the major contribution of the book is the detailed presentation of the computer aids as problem solving tools in reactor design. This naturally leads to application to more realistic problems as opposed to simplified artificial schemes such as $A \rightarrow B$. This book is therefore able to focus on the applications to practical industrial

problems.

Chapter 1 introduces the basic concepts as applied to simple reactions and ideal reactors. The rate of reaction is nicely defined on a unit stoichiometric basis, and the rate of formation of any given species is then related to this quantity by using the stoichiometric coefficients. Such an approach is necessary for computer based simulations of more complex systems.

Chapter 2 extends the basic concepts for more complex reaction schemes. The Runge-Kutta method for solving a set of differential equations is introduced here and then applied to a number of problems for plug flow reactors. The analysis to a general reaction network is introduced on the basis of a matrix formulation. The Concepts of rank of matrix and its use in determining the key limiting reactants is briefly presented. It would have been useful to elaborate on these concepts in somewhat more detail with additional solved problems because the students usually have difficulties in this area.

Chapter 3 introduces the solution methods for different reactor types. The Newton-Raphson method for solving a set of nonlinear algebraic equations is discussed and the application to a perfectly mixed reactor handling a complex kinetic scheme is nicely presented. Chapter 4 deals with the additional complications of thermal effects. Again, numerical methods are exten-

*Continued on page 49.***1989****Chemical
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AN EXPERIMENT IN AUTOTROPHIC FERMENTATION

Microbial Oxidation of Hydrogen Sulfide

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THERE HAS BEEN AN increasing effort in recent years to introduce chemical engineering students to biological processes. These efforts may be rather modest, with the incorporation of one or more experiments in enzyme kinetics or fermentation into the undergraduate laboratory, or more broadly based with formal course work in microbiology, biochemistry and biochemical engineering, and blocks of time in the laboratory devoted to bioengineering experiments. However, even in the more comprehensive programs the chemical engineering student is typically exposed to only one basic type of fermentation, that which is based on heterotrophic metabolism. In other words, the microorganisms which make up the fermentation culture utilize *organic* compounds as carbon sources and light or the oxidation of organic compounds as a source



Kerry L. Sublette obtained his BS in chemistry from the University of Arkansas, his MS in biochemistry from the University of Oklahoma, and his MSE and PhD in chemical engineering from the University of Tulsa. After six years in research and development with Combustion Engineering, he joined the chemical engineering faculty at the University of Tulsa in 1986. His research interests are in fermentation, biocatalysis, microbial desulfurization of coal, and biological methods of hazardous waste treatment.

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TABLE 1
Medium for Anaerobic Growth of *Thiobacillus denitrificans*

COMPONENT	PER LITER
Na ₂ HPO ₄	1.2 g
KH ₂ PO ₄	1.8 g
MgSO ₄ ·7H ₂ O	0.4 g
NH ₄ Cl	0.5 g
CaCl ₂	0.03 g
MnSO ₄	0.02 g
FeCl ₃	0.02 g
NaHCO ₃	1.0 g
KNO ₃	5.0 g
Na ₂ S ₂ O ₃ or H ₂ S(g)	10.0 g (thiosulfate)
Trace metal solution*	15.0 ml
Mineral water	50.0 ml

* See reference (2).

of energy. Another way of life exists by which microorganisms may derive both carbon and energy from inorganic sources. This is termed autotrophic metabolism. Autotrophic organisms are becoming increasingly important commercially in waste treatment, coal and sour gas desulfurization, and mineral leaching applications. This experiment is designed to introduce the student to fermentation based on autotrophic metabolism. The subject of substrate inhibition is also addressed. This experiment is not recommended as a first introduction to fermentation but as a demonstration of the wide range of metabolic capabilities of microorganisms.

Specifically this experiment utilizes the autotrophic bacterium *Thiobacillus denitrificans* to anaerobically oxidize H₂S(g) to sulfate in a batch stirred tank reactor. Hydrogen sulfide is shown to be an inhibitory substrate for the bacterium; however, under sulfide-limiting conditions rapid and complete oxidation of H₂S is observed with undetectable levels of H₂S

in the bioreactor outlet gas. Provided the bioreactor can be sampled periodically over 1-2 days, the stoichiometry of the reaction is readily determined.

BACKGROUND

In nature there exists a large and widely distributed group of microorganisms which play a central role in the maintenance of the carbon, nitrogen, and sulfur cycles. These microorganisms are termed lithotrophic if they are capable of deriving energy and/or reducing equivalents from the oxidation of inorganic compounds. Chemolithotrophs derive both energy and reducing equivalents from such reactions, while photolithotrophs derive energy from the absorption of radiant energy and reducing equivalents from oxidation of inorganic compounds. Those microorganisms capable of also deriving carbon for biosynthesis from an inorganic source (carbon dioxide) are termed autotrophic. Examples of inorganic energy sources for chemoautotrophs include hydrogen, ammonia, iron (II) salts, elemental sulfur, thiosulfates, and sulfides. The interrelationship between substrate oxidation and biosynthesis in chemoautotrophic organisms is illustrated in Figure 1.

Thiobacillus denitrificans is a strict autotroph and facultative anaerobe first described in detail by Baalsrud and Baalsrud [1]. Thiosulfate, elemental sulfur, and soluble sulfide may be utilized as energy sources with oxidation to sulfate. Under anaerobic conditions nitrate may be used as a terminal electron acceptor with reduction to elemental nitrogen.

Anaerobic growth of *T. denitrificans* on $H_2S(g)$ has been described in detail by Sublette and Sylvester [2-4]. The medium used to grow *T. denitrificans* is given in Table 1. When H_2S served as the energy source it was bubbled into the reactor at a rate sufficiently low as to maintain sulfide-limiting conditions. In other words, H_2S was introduced into the cultures at a rate which was less than the maximum oxidation capacity

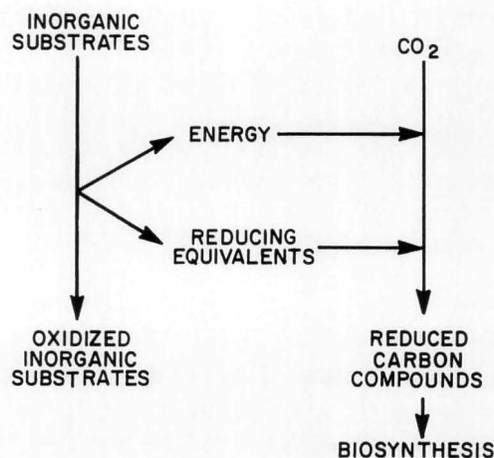


FIGURE 1. Chemoautotrophic metabolism

of the biomass. Stock cultures and start-up cultures used thiosulfate as an energy source. Under anaerobic conditions nitrate was the terminal electron acceptor. Bicarbonate was the carbon source and ammonium the source of reduced nitrogen. The medium also contained a phosphate buffer and sources of various essential mineral nutrients.

Sublette and Sylvester [2, 3] reported that when $H_2S(g)$ was introduced into anaerobic cultures of *T. denitrificans* previously grown on thiosulfate, the H_2S was immediately metabolized with no apparent lag. Typically the feed gas contained about one mole percent H_2S . Initial loadings were in the range of 4-5 mmoles $H_2S/hr-g$ biomass. With sufficient agitation to reduce the average bubble diameter to about 0.25 cm and gas-liquid contact times of 1-2 sec, H_2S was undetectable in the reactor outlet gas by GC/MS. Less than $1 \mu M$ of total sulfide (H_2S , HS^- , S^{2-}) was observed in the reactor medium during periods of up to thirty-six hours of batch operation. No intermediates of sulfide oxidation (elemental sulfur or sulfite) were detected; however, sulfate accumulated in the reactor medium as H_2S was removed from the feed gas. Oxidation of H_2S to sulfate was accompanied by growth as indicated by an increase in optical density and protein concentration and a decrease in the NH_4^+ concentration in the medium. The reaction was acid producing requiring hydroxide (OH^-) equivalents to be pumped into the reactor to maintain an optimum pH of 7.0. Small amounts ($< 40 \mu M$) of nitrous oxide, N_2O , could be detected in the reactor outlet gas. However, no other intermediates of nitrate reduction were observed to accumulate while nitrate was consumed. The stoichiometry of anaerobic H_2S oxidation by *T. denitrificans* in batch reactors as reported by Sublette and Sylvester [2] is given in Table 2.

Sublette and Sylvester [2] also reported that H_2S

TABLE 2
Stoichiometry of Anaerobic H_2S Oxidation by
T. denitrificans in Batch Reactors*

SO_4^{2-}/H_2S	1.04	mole/mole
NO_3^-/H_2S	1.36	mole/mole
NH_4^+/H_2S	0.12	mole/mole
OH^-/H_2S	1.60	equivalents/mole
Biomass/ H_2S	12.1	g/mole

* Average of four determinations

is an inhibitory substrate for *T. denitrificans*. Inhibitory effects were observed at total sulfide concentrations as low as 200 μM with total inhibition observed at 1000 μM . The total sulfide concentration in the medium of batch anaerobic *T. denitrificans* reactors operated under sulfide-limiting conditions was well below inhibitory levels. However, these authors reported that if the maximum capacity of the biomass for H_2S oxidation was exceeded, inhibitory levels of sulfide quickly accumulated in the medium. This upset condition was characterized by H_2S breakthrough in the outlet gas, release of large amounts of N_2O and accumulation of elemental sulfur in the medium. It was observed that this upset condition was reversible if the cultures were not exposed to the accumulated sulfide for more than two to three hours. Reduction in the H_2S feed rate following an upset condition reduced the H_2S and N_2O concentrations in the outlet gas to pre-upset levels with elemental sulfur oxidized to sulfate. The H_2S loading at which the specific activity of the *T. denitrificans* biomass was exceeded resulting in upset was observed to be 5.4-7.6 mmoles $\text{H}_2\text{S}/\text{hr-g}$ biomass under anaerobic conditions.

The autotrophic medium described in Table 1 will not support the growth of heterotrophs since there is no organic carbon source. However, Sublette and Sylvester [4] observed that if aseptic conditions were not maintained a heterotrophic contamination developed in a *T. denitrificans* culture growing on thiosulfate or H_2S . Evidently *T. denitrificans* releases organic material into the medium in the normal course of growth or through lysis of nonviable cells which supports the growth of heterotrophs. Sublette and Sylvester reported that the heterotrophic contamination had no discernable effect on H_2S metabolism by *T. denitrificans*.

EXPERIMENTAL PROCEDURE

Samples of *Thiobacillus denitrificans* may be obtained from the American Type Culture Collection, Rockville, Maryland, or from the author. Stock cultures may be grown anaerobically on thiosulfate in 10 ml culture tubes at 30°C. When dense growth appears (three to four days with fresh inoculum) store at 4°C until used. Stocks should be transferred every thirty to sixty days to maintain vigorous cultures. Stock cultures do not need to be grown aseptically. Figure 2 presents a schematic diagram of the equipment required to culture *T. denitrificans* anaerobically on $\text{H}_2\text{S}(\text{g})$.

An investigation of the anaerobic oxidation of H_2S by *T. denitrificans* is described below. Details of the analytical methods required for a thorough study of

the stoichiometry of the process are also presented. It is intended that the experiment can be used to introduce the subjects of autotrophic fermentation and substrate inhibition at a number of levels of difficulty and challenge to the students. A straightforward demonstration of the detoxification of a hazardous material by a bacterium can be conducted requiring less than three hours of student participation. However, an investigation of the stoichiometry of the process would require intermittent observation and sampling of H_2S cultures for one to two days plus time for sample analysis.

Before describing the experimental protocol a word of caution is in order. Hydrogen sulfide is a highly toxic gas. The threshold limit value (time weighted average) for H_2S exposure is 10 ppm (7-8 hrs). The threshold limit value for short term exposure is 15 ppm (15 minutes). It is therefore necessary that the laboratory instructor carefully monitor all operations involving H_2S and, as indicated in Figure 2, the entire fermentation system *must* be located in a fume hood.

Anaerobic Oxidation of H_2S

A working culture of *T. denitrificans* may be developed by growing on thiosulfate at 30°C and pH 7.0 using the medium described in Table 1. The purpose of this prior cultivation on thiosulfate is to develop a sufficient concentration of biomass in the reactor so that an appreciable rate of H_2S can be fed to the reactor without exceeding the biooxidation capabilities of the biomass. Otherwise sulfide would accumulate in the reactor medium to toxic levels.

The recommended culture vessel (see Figure 2) is a 1-2 l jacketed beaker with a large silicone rubber

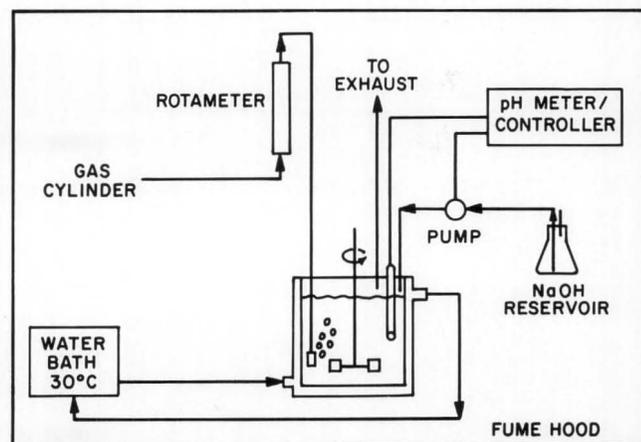


FIGURE 2. Schematic diagram of equipment required to culture *T. denitrificans* anaerobically on $\text{H}_2\text{S}(\text{g})$

Chemolithotrophs derive both energy and reducing equivalents from such reactions, while photolithotrophs derive energy from the absorption of radiant energy and reducing equivalents from oxidation of inorganic compounds. Those microorganisms capable of also deriving carbon for biosynthesis from an inorganic source (carbon dioxide) are termed autotrophic.

stopper to support probes and inlet and outlet ports. Temperature may be controlled by circulating water at 30°C through the jacket of the reactor. The pH may be monitored and controlled by a pH meter/controller which activates a peristaltic pump to deliver 6 N NaOH to neutralize acid produced by the biooxidation of thiosulfate or H₂S. A pH stability of ± 0.2 units is desirable. If the controller also activates a laboratory timer, the rate of NaOH addition can be monitored. A gas feed of 5 mole % CO₂ in nitrogen at 30 ml/min is recommended during growth on thiosulfate to ensure the continuous availability of a carbon source. Gas mixtures are fed to the reactors from cylinders of compressed gas through two stage stainless steel regulators and rotameters. Gas is introduced into the culture medium by means of a glass fritted sparger. A four or six bladed, flat disk impeller may be used for agitation at 200-300 rpm to produce good gas-liquid contacting.

As noted previously, heterotrophic contamination has little or no effect on the growth of *T. denitrificans* in an autotrophic medium. Therefore, it is not necessary to sterilize the reactor or any associated equipment.

When 1-2 l of thiosulfate medium is inoculated with 20 ml of a fresh stock culture, a working culture is produced in approximately sixty hours. The medium described in Table 1 is nitrate limiting; therefore, when the nitrate is depleted the culture stops growing. At this point the culture will have an optical density at 460 nm of about 1.0.

The pathways for sulfide and thiosulfate oxidation to sulfate in *T. denitrificans* are not independent but have two common intermediates [5]. In the presence of thiosulfate the rate of sulfide oxidation would be reduced because of competition between intermediates of thiosulfate and sulfide oxidation for the same enzymes of the sulfur pathway. Therefore, prior to the introduction of H₂S to *T. denitrificans* cultures, residual thiosulfate must be removed. This may be accomplished by sedimenting the cells by centrifugation at 4900 × g for ten minutes at 25°C. A refrigerated centrifuge is preferred. However, any centrifuge is acceptable if the temperature of the cell suspension does not exceed 45°C during harvesting. The supernatant is discarded and the cells resuspended in growth medium without thiosulfate. Following a second centrifugation the washed cells are resuspended in

medium without thiosulfate and transferred back to the reactor. It is recommended that the reactor and all probes be rinsed in distilled water to remove residual thiosulfate prior to reintroduction of cells.

Once thiosulfate has been eliminated, hydrogen sulfide can now be introduced into the culture by changing the feed gas to include H₂S. A composition of 1 mole % H₂S, 5 mole % CO₂ and balance N₂ is recommended. If the OD₄₆₀ of the culture is at least 0.8, a feed rate of about 50 ml/min will not exceed the biooxidation capabilities of the culture. It is recommended that the H₂S feed rate be brought to this level stepwise over about thirty minutes. With proper agitation to achieve good gas-liquid contacting, H₂S will be undetectable in the gas outlet of the reactor.

The stoichiometry of anaerobic oxidation of H₂S(g) by *T. denitrificans* can be obtained by sampling the reactor contents over a period of 24-48 hours as H₂S is removed from the feed gas. Of particular interest would be the concentrations of sulfate (SO₄⁻²), nitrate (NO₃⁻), ammonium ion (NH₄⁺), elemental sulfur and biomass in the reactor medium. Analytical methods are discussed below.

The inhibitory nature of H₂S as a substrate can be demonstrated by increasing the H₂S feed rate stepwise until H₂S breakthrough is seen. When breakthrough occurs, nitrous oxide (N₂O) will also be detected in the outlet gas and elemental sulfur seen to accumulate in the reactor medium. Sulfur will give the medium a milky white color. As described in a previous section, the upset condition is reversible if not prolonged. However, if the upset condition is allowed to persist the outlet H₂S concentration becomes equal to the inlet, indicating complete loss of biooxidation activity in the culture.

Analytical

Feed gas and reactor outlet gas may be analyzed for H₂S and N₂O by gas chromatography. Using a thermal conductivity detector the detection limit for H₂S is about 2-4 μM with a 0.25 ml sample. In our laboratory a 10-ft by 1/8-in ID Teflon column containing Porapak QS (Waters Associates) has been used with a helium flow rate of 20 ml/min. A column temperature of 70°C and injector and detector temperatures of 200°C are satisfactory. Under these conditions the retention times of N₂, CO₂, N₂O, and H₂S are 0.8, 1.8,

2.2, and 5.3 minutes, respectively. H_2S is quantitated by comparing chromatograms of samples to chromatograms produced by a certified primary standard (Matheson Gas Co.). If a gas chromatograph is unavailable, H_2S and N_2O may also be determined to $\pm 25\%$ using Gastec Analyzer Tubes (Yokohama, Japan).

Nitrate may be determined in thiosulfate free samples by the cadmium reduction method [6]. Ammonium ion may be determined by the Nessler method without distillation [6]. Sulfate is readily determined turbidometrically [6]. Premeasured reagents for these analyses may be purchased from Hach Chemical Co.

Thiosulfate may be determined by titration with standard iodine solution using a starch indicator [7]. Elemental sulfur may be collected by filtration on 0.45 micron Millipore Type HA filters and determined by reaction with cyanide to produce thiocyanate. Thiocyanate may be quantitated as $Fe(SCN)_6^{-3}$ which has a molar extinction coefficient in water at 450 nm of $3.37 \times 10^3 M^{-1} cm^{-1}$ [8].

Biomass may be determined in terms of whole cell protein by sonication followed by colorimetric analysis by the micro modification of the Folin-Ciocalteu method [9, 10]. (Folin-Ciocalteu reagent may be purchased from Anderson Laboratories.) Cells are suspended in 10-20 ml of 20 mM phosphate buffer, pH 7.0, and sonicated with a sonic probe until the suspension is clarified. In our laboratory a Braun-Sonic 1510 with a 3/4 in. probe is used at 150 watts for two three-minute periods with intermittent cooling. The resulting protein solution is analyzed directly without further treatment. Bovine serum albumin (Sigma Chemical Co.) is used as a standard. The protein content of *T. denitrificans* cells grown on $H_2S(g)$ is $60 \pm 3\%$ [2]. Using this figure the results of protein analyses may be converted to dry weight *T. denitrificans* biomass.

SAMPLE RESULTS

In a typical batch experiment the oxidation of 18.3 mmoles of H_2S was accompanied by the production of 18.8 mmoles sulfate and 246 mg of biomass. A total of 27.0 mmoles nitrate, 2.2 mmoles ammonium ion and 31.8 meq of hydroxide ion were utilized.

Figures 3a and 3b summarize the results of analysis of the medium of an anaerobic reactor as H_2S is oxidized by the culture. Sulfate is seen to accumulate in the medium. The concentration of biomass increases as the cells grow using H_2S as an energy source and correspondingly the optical density increases with time. Nutrient levels (NO_3^- and NH_4^+) decline as H_2S

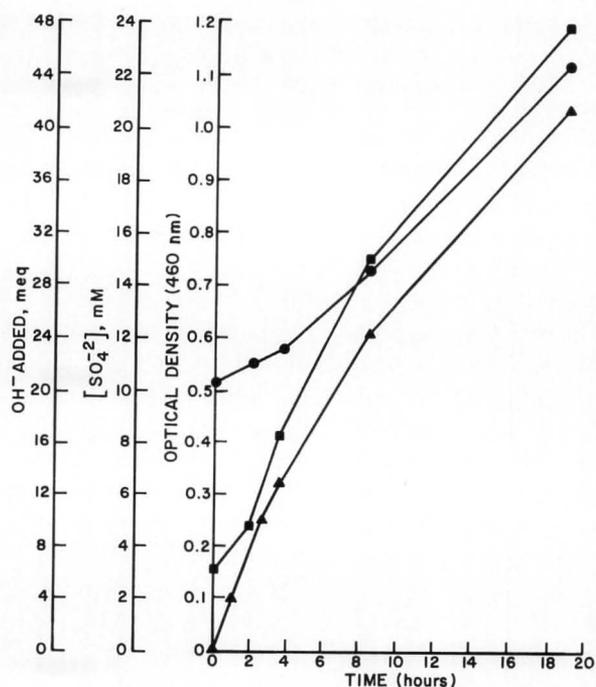


FIGURE 3a. Optical density, concentration of sulfate (SO_4^{2-}) and hydroxide ion (OH^-) utilized in an anaerobic *T. denitrificans* batch reactor receiving 1.25 mmoles/hr hydrogen sulfide (H_2S) feed. OD (●); SO_4^{2-} (■); OH^- (▲).

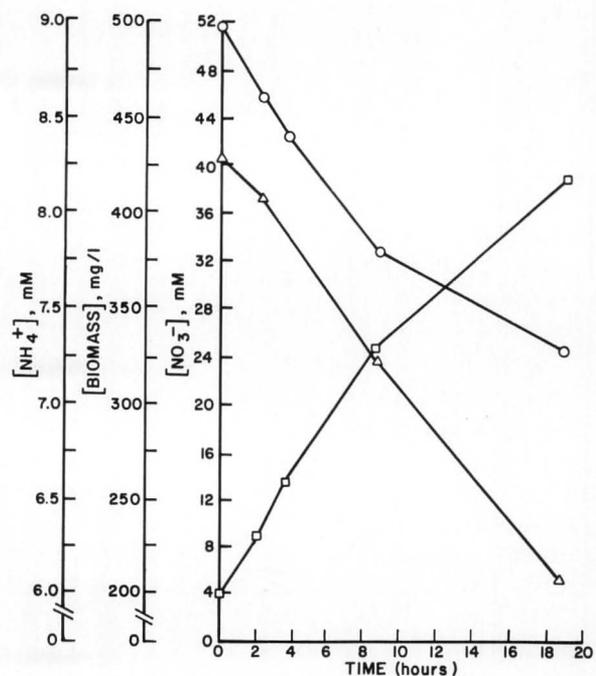


FIGURE 3b. Concentrations of nitrate (NO_3^-), biomass and ammonium (NH_4^+) in an anaerobic *T. denitrificans* batch reactor receiving 1.25 mmoles/hr hydrogen sulfide (H_2S) feed. NO_3^- (○); NH_4^+ (▲); biomass (□).

is oxidized and the cell population increases. Lastly, hydroxide is steadily consumed as acid is produced by the process.

ACKNOWLEDGEMENT

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ChE book reviews

ADVANCES IN DRYING,

Volume 4

Edited by Arun A. Mujumdar

Hemisphere Publishing Corporation,

79 Madison Avenue, New York, NY 10016

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Reviewed by

E. Johansen Crosby

University of Wisconsin

The drying of solids is probably one of the oldest unit operations practiced by man. In the past, this process generally was considered to mean the removal of moisture from matter when the amount of same was relatively small. However, in the chemical processing industry of today, feedstocks to be dried may contain as much as ninety percent moisture, and that moisture many times may be nonaqueous and multicomponent. Moisture removal can be effected by (i) condensed-phase separation, (ii) chemical decomposition, (iii) chemical precipitation, (iv) absorption, (v) adsorption, (vi) expression and (vii) vaporization. Convection drying, *i.e.*, moisture removal by vaporization with the drying medium being both the energy source and moisture sink, is by far the most common method used. The materials-handling considerations resulting from many different feedstock and product requirements inevitably resulted in the development of many types of equipment—each with its own operation idiosyncrasies.

In recent years, the number of monographs, handbooks, journals, proceedings and research reports devoted to this subject has increased markedly with the series entitled *Advances in Drying* which was initiated in 1980. In the preface of Volume 4, the editor indicates that this ". . . series is designed to allow individuals concerned with (various) aspects of drying to access relevant information in a carefully reviewed form with minimal time and effort." Like its predecessors, this work consists of a number of reviews, updates, and developments concerning theory, design, and practice in connection with moisture transfer through and/or removal from solids. Eight individual topics are addressed from various viewpoints by contributors from seven countries.

Computer-aided design of convection dryers is discussed in Chapter 1. The classification of mathematical models according to contact zones and flow patterns, the systematic application of the overall mass and energy balances, and the simplification of drying mechanisms is presented. Most of the chapter is devoted to examples of recommended calculation procedures for different types of dryers with the coverage of spray and rotary dryers being especially minimal. Chapter 2 deals with recent advances in the drying of wood. A review of drying theory and modeling is followed by a good summary of recent developments in lumber and veneer drying. Recommendations for future work are presented. Chapter 3 contains a condensed theoretical review of the drying of porous solids with stress on the internal mechanism of moisture and energy transfer. Coupled heat and moisture transfer in soil is reviewed in Chapter 4. Written from

Continued on page 43.

EXPERIENCING TEAM RESPONSIBILITY IN CLASS*

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THE ABILITY TO effectively manage a project within a team of peers is one signature of a professional—one which is often ignored in engineering education. However, such an experience *can* be successfully woven into the curriculum to the enhancement of technical fundamentals.

Even as an entry-level engineer, a person must plan, schedule, and then coordinate the work of operators and technicians in adjacent groups. Soon thereafter, one plans, influences priorities, and coordinates peers' activities across organizational boundaries. In any case, that one person is solely responsible for timely results; but he or she must rely on the contribution of others, must accommodate the priorities of others, must foster effective interper-



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*Presented at the 1987 annual AIChE meeting November 17, 1987, in New York, NY

TABLE 1
Rules

The project descriptions I have written are suggestions based on my experience, but may be changed. As you progress you will find many other aspects of your topic and you will want to pursue those that interest you. If you want to change the project scope, however, be sure to coordinate that action with me. In any event, you need to meet with me to ensure that your plans meet my expectations.

I will grade the written report. It should be neat, organized, and presented so that it teaches a technology or demonstrates an application. Make it something which can be useful to you five years from now. The grade will be weighted 50/50 on technical accuracy and completeness and on communication effectiveness (logical presentation, writing clarity, organization).

The written reports should be 15 to 25 handwritten, single-spaced, or typed, double-spaced pages, including examples, figures, derivations, and computer code. Don't go for broke...this is just a one-month project. But do present some meaningful and useful work.

On the due date the leader will present a ten-minute oral report for the class. The oral report will not be graded.

Take care of your group members. Plan ahead so they can plan their own work schedule. Assign portions of the project that interest them so that they do their best work for you. Use your group members. Delegate, or else you will overwork yourself trying to meet my expectations.

Use me as a consultant for personnel problems as well as technical methodology.

sonal relations, and has input into the performance rating of others. Key skills of a practicing engineer include planning, communicating, interaction management, accommodating, and listening. Key perspectives include project ownership and accountability. Such professional attributes, however, are not usually descriptive of an engineer's formal education.

It is likely that at least 50% of an engineer's effectiveness will depend on human team interaction skills. However, the academic experience is largely individualistic, and even the scant group exercises in lab and design are often without assigned leadership responsibility and authority. In practice, a design engineer must cooperate with others; for instance, he must rely on an R&D engineer to generate design data for his project. But we teach and test for *indi-*

vidual performance. A process engineer must get the cooperation of a production staff to run trials, and he must rely on lab services to analyze the results. Yet, throughout his education, we have encouraged, rewarded, and prepared the graduate for individual performance. Consequently, a student's perspective on the practice of engineering is usually misdirected.

If education means developing life skills in preparation for social responsibility (as opposed to merely developing a technical facility), then it is our responsibility as professors to move beyond a technical/academic focus and to incorporate life-relevant experiences into the classroom. Success at human management is a requirement for successful technology implementation. As faculty who are concerned with individual technical performance, we are sometimes unaware that we have omitted the development of the interpersonal skills required for effective engineering.

The objectives of the in-class team responsibility project are:

- To integrate some of these professional perspectives into the classroom
- To coach students toward improved project and people management effectiveness
- To support the traditional educational objectives
- To enjoy the experience.

As faculty who are concerned with individual technical performance, we are sometimes unaware that we have omitted the development of the interpersonal skills required for effective engineering.

ASSIGNMENT STRUCTURE AND RULES

Each student in the class becomes a project team leader once and chooses a project topic from a prepared list. The project will take about a month to complete and will demonstrate relevant engineering skills. Projects have included writing computer simulators, technology reviews, a mini chapter for a text, and conducting personnel surveys. The assignment statement is shown in Table 1, and Table 2 lists the project titles given to the students in a junior heat transport course. (While the topics in the third section of Table 2 are non-technical, I think that they are important to engineering success and, therefore, relevant to the education of an engineer.)

Three other classmates are assigned to the project leader as team members. Each student is a team leader once and participates in a total of four projects. The team leader has sole responsibility for the project scope, its planning, work distribution, daily coordination, and for both the written and oral presentations. (The oral is required but not graded.) The leader

TABLE 2
List of Projects for a Junior Heat Transport Course

Write a computer simulator and run "trials" of

- A binary boiler
- A condenser
- A red-hot quench
- The transient conduction in a rod
- The steady state temperature profile in a slab of non-constant thermal conductivity
- The steady state performance of a shell-and-tube liquid/liquid heat exchanger
- The steady state temperature distribution in a fin of non-constant cross sectional area
- A steam traced pipeline
- The transient response of a temperature detector in a thermowell with external conduction

Write a technology report, a mini-chapter in a text, presenting an overview of the topic, design equations, and original examples of

- Natural convection
- Heat pipes
- Coiled heat exchangers
- Alternate boiling/condensing heat transfer fluids
- Engineering/business economics
- Heat transfer in two-phase flowing fluid
- Human perception of hot and cold

- Mechanical design criteria for baffles
- Dehumidifiers and after-coolers
- Thermosiphon and calendria reboilers
- Insulation
- Developing and validating correlations
- Steam tracing
- Evaporators/cooling towers
- Temperature measurement device technology and calibration

Write a mini-chapter to introduce the relevance and the engineering skills associated with

- Systematic diagnosis of process faults
 - The transition from student to engineer
 - Critical thinking to recognize and demythify technical folklore
 - Personality development and inappropriate adult behavior
 - Decision analysis
 - Creativity
 - Social structure within human institutions
 - Perception of performance
 - Industrial performance reward systems
 - Temptations and attitudes that lead to less than desirable engineering quality
 - The balance of power: marketing, finance, or engineering?
-

The nature of such an assignment is quite different from the highly structured, individual, deterministic, short-term, private type assignment for which the student has been programmed during his previous fifteen years of school. It is important that the students are comfortable with the change.

meets with me to learn what my expectations of an appropriate project scope are, but then makes the final decisions himself. The project grade is assigned exclusively to the team leader; however, the leader grades his team members. My grade of the project contributes 15% to the leader's course grade, and each of the three grades he receives as a team member counts 5%. The combined four-project grade is 30% of the course grade.

Projects are assigned near the beginning of the semester but are due about one month after the fundamentals of a topic are covered in class lecture. The projects require sustained effort during the last two-thirds of the semester, and I reduce the extent of weekly homework assignments as a result. Topics from the last three weeks' lectures are not assigned as projects. Students select their own project choices from a list of topics that I have prepared. Students can suggest other topics, but rarely do they have that foresight in an unfamiliar technology. Not all of the topics are specific to the course technology, but I judge all to be relevant to the practice of engineering (*e.g.*, engineering economics, human perception of hot and cold, systematic trouble diagnosis, debunking of technical folklore). I match project leaders to one of their first project choices and then assign other team members in order to distribute their project due-dates throughout the semester. I then assign other members so that each student works on at least one project of each type (computer simulator or report) and finally, to shuffle personnel as much as possible.

PREPARATION FOR SELF AND CLASS: A REQUIREMENT

The nature of such an assignment is quite different from the highly structured, individual, deterministic, short-term, private type assignment for which the student has been programmed during his previous fifteen years of school. It is important that the students are comfortable with the change. As adults they can choose to put their personal energy where they perceive it to benefit them the most, and it is important that they "buy into" the objectives of this new type of assignment. So, distributed over several early lectures, I spend about one-half of a class previewing the assignment, discussing the engineering work environment, discussing the experiences I want them to be prepared for, presenting the objectives of the particular assignment, and offering assurances of my avail-

ability as both a personnel and a technical consultant. As projects are in progress, I spend five minutes here and five minutes there discussing group assignment plans, coordination, flexibility, ways to handle intractable "employees" and other skills that I perceive are relevant. I also reinforce the workplace/classroom differences to periodically justify the project strangeness in order to keep the adults "on board."

Problems occasionally arise: a failing student decides to put his energy into other courses and fails to contribute his share to the leader's project; a leader plans too late and then unreasonably expects group members to perform at a high level regardless of their other commitments; one project turns out to be much more difficult than the others. It requires a self-confident professor to calm the slighted student's panic, to be flexible, and to assure students that, in spite of individual situations, subjective grading can be fair. The professor must be willing and able to manage such common personnel situations as when a student feels that events beyond his control will affect the reward of his personal performance. These are common workplace problems which a practicing engineer must handle and that a student can preview in his education. Success at human management is a requirement for successful technology implementation.

RESULTS

Comments from the semester-end student course evaluations are one source of results. Verbatim they include:

- The independent research is a *great* learning experience—*keep it!*
- Leading a team is *super*, have to deal w/ people not willing to do their part and taking all the input & putting it into 1 report.
- Learned TONS! I think it will be very helpful later on.
- The [independent] research is a good change from number crunching.
- I learned that I need work on my organizational skills.
- It is hard grading fellow classmates— *but* good experience.
- Also learned a few more things on my own.
- I enjoyed working as a team, it helped bring us closer together, and we learn more through research [independent study].

- . . . has given us a big opportunity to learn to work together and to be a responsible person in every aspect.
- Heat transfer concepts as well as fundamental human interactions were taught.
- Required and inspired creative thinking in solving practical engineering problems.
- I'm glad projects were assigned. They brought a special type of learning into the course.
- Keep it.
- Do it again next year.

Overall, the positive evaluations (70%) outnumber the negative evaluations (8%) by 9 to 1. The negative comments concern either the unfairness in student grading or the variable difficulty of the computer versus the independent study type of projects. I will address these complaints later. The ambivalent responses, such as "grading of the projects was fair," or "give more time to complete the projects," comprised 22% of the evaluation. The students felt that the exercise achieved the desired results. So did I.

Along with my personal perception that the exercise met its objectives, there has been one outstanding tangible result. One student chose to investigate the on-the-job transition one must make in the student-to-engineer metamorphosis. Her group augmented their literature review with personal interviews and a mail survey to our graduates with two to five years' work experience. The questionnaire was developed after their initial investigations and focused on the sufficiency and relevance of engineering education to the skills necessary for life and the practice of engineering. The project report was excellent. It was accepted for publication in the Texas Tech engineering student journal [1].

DISCUSSION

I think that such an exercise is appropriate to the maturity level and stability of juniors, seniors, and graduates. I would anticipate that the mid-term drop-out rate and marginal commitment of many freshmen and sophomores would create severe personnel problems if such an assignment was included at their level.

The 15% and 5% grading schedule provides sufficient incentives. The leader wants a quality report and must rely on substantial team member contributions to meet my expectations. Additionally, the appearance of the half-letter grade control that the leader has provides sufficient incentive to the member for quality participation. In actuality, however, members receive contribution grades from A to D—at

worst a sixth of a course letter grade per project. In effect, as professor I really give up very little course grade assignment authority.

With the 15% and three 5% project grades and with homework counted as 20%, non-test grades count 50% of the course grade. Tests count as the remaining 50%. I have no problem with that weighting; however, students occasionally suggest that tests should count more.

Initial assignment descriptions are very brief, *i.e.*, "Write a chapter on heat pipes for a heat transfer text. Describe the phenomena, uses, operating condi-

. . . there has been one outstanding tangible result. One student chose to investigate the on-the-job transition one must make in the student-to-engineer metamorphosis.

tions, and fluids. Give design equations and create examples." On that particular project, with initial research the student finds that liquid-wicking phenomena for zero-gravity applications, multicomponent VLE behavior, rarified vapor fluid dynamics, variable surface area control, and internal fins are each of application's importance. The student chooses the specific technology that he finds interesting and relevant and, together with me, works out a project scope that meets my expectations and my realization of the limits of a month-long project that counts 15% of one course in one semester.

I have not yet graded the oral presentations. To some it is an intimidating event, and I wanted to create a pressureless environment for the verbal class presentation. Additionally, I did not want the students to compete for fancy visual aids. However, the oral presentations were often ill-prepared and of no use to the other class members. In the course evaluations, a few students suggested grading the oral presentation as a portion of the project grade and I plan to try it next time.

A recurring student suggestion is that more time should be allowed for completion of the projects. I suspect, however, that some students shoot for substantial results and completeness, enjoy the independence, and would write a book if allowed. I also suspect that others get started late and would never have enough time. Considering the planning and delegation experiences I want to create, and the justifiable time demand of the project portion of one course, I think that the one-month duration is appropriate. Before students err, however, it is necessary to preview these time constraint aspects. The students must be made aware of the need to limit project scope, to delegate, and to start early.

The reports submitted at the end of the semester benefit from the grading, comments, and in-class discussions on the earlier reports. In spite of my previews, the initial projects are at a grading disadvantage. The students also come to recognize this, and to be fair, I add a letter grade to projects due early in the semester. The students seem satisfied. I have reserved this option and keep it unannounced until I grade the second set of projects, but I have felt that it is appropriate each semester.

Students have a tendency to do most of their own project work. Perhaps it is educational inertia. Leaders' estimates of their personal effort ranged from 50% to 90% of the total group effort. Delegation and coordination are important job functions and, in discussions with leaders, I have encouraged them to delegate. Although I am satisfied with the average leader contribution of 75%, I would prefer to push that to 60% and in subsequent classes will help leaders identify project portions that can be delegated.

As mentioned in the results section, there were

two student criticisms of the assignment. One of the two negative evaluations concerned the assignment of grades by the student leaders, and was characteristically stated as, "People give good grades to their friends, without considering their actual work." The objection is not to the student-grading-student aspect of the exercise, but that student grading is not as objective as one would like. Although project leaders did assign D's, A's were assigned to 70% of the members' contributions, and B's to about 25% of the contributions. However, we all recognized that the inflated grades are not indicative of a member's performance and that friends may grade friends too leniently. I've discussed optional grading policies, such as pass/fail and S+/S/U with the classes. However pass/fail lacks discrimination, and the S+/S/U is too similar to A/B/C and may also be subject to grade inflation. I am now trying an alternate approach. Leaders do not grade, but fill out a "Group Member Evaluation Form" (see Table 3) for each group member. The form originated as an industrial performance review but has been

TABLE 3
Group Member Evaluation Form

NAME _____ Experiment No. _____

INSTRUCTIONS:

Place an "X" mark on each rating scale, over the descriptive phrase which most nearly describes the person being rated. *Evaluate each quality separately.* Avoid the common tendency to rate nearly everyone as "average" on every trait instead of being more critical in judgement. Also avoid another common tendency to rate the same person "excellent" on every trait or "poor" on every trait based on the overall picture one has of the person being rated.

ACCURACY is the correctness of work duties performed.

Made many errors	Somewhat careless	Avg. number of mistakes	Accurate most of the time	Exceptionally accurate
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ALERTNESS refers to the ability to grasp instructions, to learn from research and to solve problems.

Slow to catch on	Needed more than average instruction	Grasped instructions with average ability	Quick to understand and learn	Exceptionally keen and alert
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FRIENDLINESS refers basically to the ability to get along with team members.

Distant & aloof	Friendly once known by others	Warm, friendly, and sociable	Very sociable & outgoing	Excellent
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PARTICIPATION is being available for and participating in group activities.

Often absent or unavailable	Lax in availability and participation	Usually available and participating	Very prompt & regular	Outstanding, did more than share
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DEPENDABILITY is the ability to do assignments well with minimum supervision.

Quite unreliable	Sometimes required prompting	Usually did assignments on time	Very reliable	Outstanding in reliability
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JOB KNOWLEDGE is the information each individual had to know or learn in order to do his/her part in all phases of the experiment

Poorly informed	Lacked knowledge of some phases	Moderately informed	Understood all phases	Had mastery of all phases
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QUANTITY OF WORK is the amount of work done by the individual throughout the planning, conduction and documentation phases of the experiment.

Unacceptable	Did just enough to get by	Average volume of work	Did more than was required	Superior work production
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OVERALL EVALUATION in comparison with other group members.

Definitely unsatisfactory	Below average but made an effort	Did an average job	Definitely above average	Outstanding
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COMMENTS:

Group Leader _____ Date _____
Group No. _____

modified and used by laboratories in Mechanical and Chemical Engineering and Engineering Technology at Texas Tech. It contains a descriptive five-item scale on each of eight team and technology performance attributes. It also has a section for other comments. I will compile the evaluation data, use that to assign a team member grade, and share the compiled results with the team member. There are several advantages to such an approach. Student leaders can check off attributes without the bias that grading carries and, consequently, may produce a more accurate measure of their team member's performance. Additionally, discussion of the compiled data with each individual may aid coaching for improved performance. Initial feedback is positive.

The second negative evaluation concerned the variable difficulty of the projects, and a typical comment was, "How do you grade a hard program compared to an easy project?" ". . . all projects should be either programs or reports." "Don't compare apples and oranges." Students perceive that the computer projects are more difficult than the technology reports. Considering the level of computer programming expertise of our juniors, I must agree. Perhaps two-thirds of the class have forgotten both the programming language and the systematic approach to programming learned in their freshman course. They tend to write the entire program at once (without having performed hand calculations for familiarity with the procedure), then become extremely frustrated as they debug simultaneous and interconnected syntax and logic errors. Although I preview this, it remains a problem, and I plan to reducing my expectations on the computer assignment scope and strengthening my message to the computer simulator project leaders.

SUMMARY

In an attempt to integrate project management and interpersonal skills development into a junior level transport course, student project exercises were structured with one accountable leader who plans, coordinates, and grades the work of three team members. The exercise structure achieves its objectives and is received well by the students. The course professor must be prepared for the degree of subjectivity introduced and be able to manage personnel problems. Student-to-student evaluations may improve with a non-grade rating form.

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1. Everett, Gayle L., "The Transition From Student To En-

gineer," *TECHnology MAGAZINE*, (a student engineering publication of Texas Tech University, PO Box 4200, Lubbock, TX, 79409), 1986/87, pp. 10-12. □

REVIEW: Advances in Drying

Continued from page 37.

the viewpoint of the soil scientist, the equations of change for mass and energy transport, formulation of the relevant mass fluxes, consideration of the transport properties, and choice of boundary conditions are covered. Experimental measurement of the transport properties also is considered and the drying of soils by buried heat sources is discussed. A mathematical model for convective drying with the incorporation of sorption isotherms is presented in Chapter 5. This chapter is not a review but rather a research paper concerned with the drying of a porous capillary body and accompanied by a very limited bibliography. Chapter 6 is primarily a descriptive review of the solar drying of crops. After a brief discussion of drying principles, the status of solar drying technology together with equipment description is presented. This is followed by a discussion of the design features and typical performance characteristics of solar heaters for air. A very brief consideration of the relevant economics concludes the review. Certain principles of operation and design considerations for spouted-bed drying are presented in Chapter 7. Emphasis is placed on the selection of a spouted-bed system and its fluid-mechanical characteristics. Three previously published models for describing the performance of this type of dryer are summarized and compared. Chapter 8 is a nontheoretical review of press drying. The principles of operation are summarized and performance data are presented. The mechanical features of existing pilot machines and proposals for full-scale dryers as well as alternatives for improved paper densification are given.

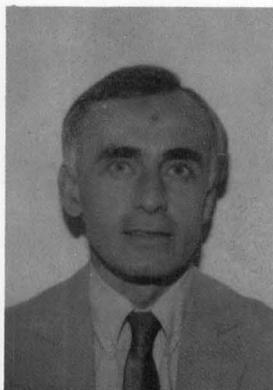
Those persons interested in drying should find the individual contributions to this volume to be of some interest. The authors of most of the chapters are generally recognized authorities in their field. Unfortunately, much of the material seems to have been edited and/or proofread very rapidly and/or poorly as there are a number of instances of quite awkward grammar, misspelling and, something especially disconcerting, incomplete nomenclature. The text is type-set and production is good except for those few figures which are reproduced by direct photocopy. As with similar publications of this type, the price is high. Because of its restricted technical content, this volume should be perused prior to purchase. □

UNSTEADY-STATE HEAT TRANSFER INVOLVING A PHASE CHANGE

An Example of a 'Project-Oriented' Undergraduate Laboratory

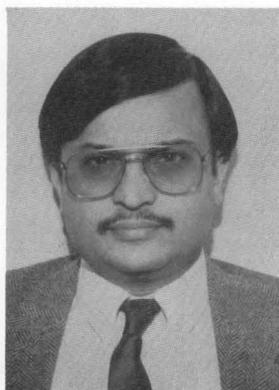
D. C. SUNDBERG and A. V. SOMESHWAR
*University of New Hampshire
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THE CHEMICAL ENGINEERING laboratory experience for undergraduate students at the University of New Hampshire is composed of a sequence of two courses which are conducted during the second semester of the junior year and the first semester of the senior year, respectively. The first course is dedicated to experimentation in the areas of fluid mechanics and heat transfer, while the second course involves mass transfer and reaction kinetics. The students have either had previous classroom courses in the subject areas involved in the laboratory or take the classroom



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Arun V. Someshwar is currently working as a research engineer with the Institute for Environmental Studies at the University of Illinois, Urbana-Champaign. After receiving his doctoral degree in chemical engineering from Michigan State University in 1982 he served on the faculty of the University of New Hampshire until July of 1988. His research interests are in the field of air pollution control, primarily in the use of electric fields and discharges for enhancing the desulfurization and denoxing of post-combustion gases. (R)



courses concurrently with the lab. The laboratory courses require the students to complete one in-depth project as well as other short-term introductory experiments in each of the subject areas. These in-depth projects have a duration of five to six weeks each, are done typically in groups of three students, involve weekly and interim group written reports, and conclude with the submission of individual written reports and group oral presentations. The oral presentations are delivered to the entire laboratory class, including the instructors. The chemical engineering faculty and graduate students are also invited to attend.

Our objectives for these in-depth projects are to require the students to become involved in the process of thoughtful and effective experimentation as an alternative to the weekly "cookbook" experiments common to their previous experience, to have them confront not-so-straightforward problems which require the generation of the bulk of the individual experiments which may need to be conducted, to have them learn to integrate theoretical approaches and experimentation to complete the project, and last but not least, to provide them with some unique opportunities to develop and demonstrate their written and oral communicational skills. In some instances we have been able to include the concepts of experimental design into the projects, while in all cases we have strongly advocated the use of theoretical models as guides to the choice of useful experiments. The unsteady-state radial freezing project described below is one which is a good example of the type of experience our students gain in their lab courses.

STRUCTURE OF THE LABORATORY PROJECT

In making up the projects for our lab courses we try to structure the assignments so that they portray a realistic problem which needs to be solved, rather than merely the experimental verification of some theoretical concept discussed in the classroom. This is not always easy, but it does make a distinctive differ-

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ence in the students' viewpoint of what the laboratory is all about. The unsteady-state radial freezing project discussed in this paper has been portrayed in the context of having to predict the radial freezing of the earth surrounding a proposed storage cavity for liquified natural gas. A copy of the project assignment sheet given to the students is shown in Table 1.

At the outset of the project we persuade the students to approach the problem by first substituting pure water for the earth surrounding the cavity and to use dry ice as a substitute for the LNG. They are rather quickly convinced that this would be an easier system to evaluate, and that with the knowledge gained here it would not be too difficult to extend the analysis to the more practical case.

Since this is a laboratory course, the students naturally think towards experimental equipment, and so they quite rapidly decide upon an arrangement of the type shown in Figure 1. Once this is in place we can discuss with them some of the problems associated with carrying out good experiments, such as insulating the top of the tank and the water bath, choosing an appropriate temperature at which to keep the liquid water, and developing enough data to not only provide information about the thickness of the ice and

TABLE 1
Project Assignment Sheet

TO: Ms. Curie, Mr. Fermi, and Mr. Einstein
FROM: Dr. Jekylhyde and the ChE Staff
RE: ChE 612 Project II

The company in which you are employed manufactures liquified natural gas (LNG) and stores it in underground caverns which amount to nothing more than large holes in the ground with suitable linings. When the extremely cold liquid contacts the earth, it freezes the moisture in the soil and a relatively impervious liner is built up around the LNG. The energy removed from the soil is taken up by the LNG and results in some vaporization of the liquid.

In order to project the extent of freezing in the surrounding earth, to gauge its time dependency, and estimate the rate of liquid vaporization, your group is asked to develop a laboratory prototype unit in which such an event might be studied. It is suggested that a simple system could be constructed using isopropanol/dry ice as a constant temperature vaporizable fluid (at -78.4°C) contained in a metal cylinder surrounded by water. The water would freeze around the cylinder and the front of the freezing zone would progress outward with time. Thermocouples could be placed at various intervals throughout the surrounding water and the temperature, as well as the freezing zone front, could be measured as a function of time. The rate of gas liberation could also be measured. A mathematical model would be useful for interpreting the above data and to make projections in the actual application to LNG. More specifically, on the basis of your model, you are to predict important details pertaining to the storage of LNG in a 20 ft. deep well, 10 ft. in diameter, and surrounded by earth with a moisture content of 10%.

Our objectives for these in-depth projects are to require the students to become involved in the process of thoughtful and effective experimentation as an alternative to the weekly "cookbook" experiments common to their previous experience.

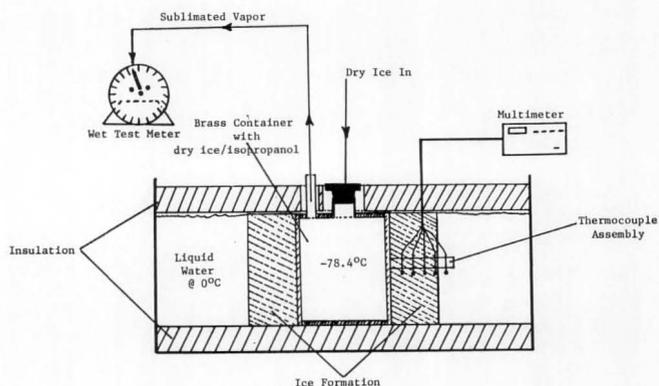


FIGURE 1. Overall schematic of tank and ice front

the temperature profile in it, but also to be able to close an energy balance. The latter point is stressed in order to get the students to realize that they can provide internal checks on the reliability of the data, in addition to its reproducibility. The sublimated CO_2 is normally directed through a wet test meter in order to measure its volumetric flowrate and the students quickly realize that they need to understand how such an instrument works in order to convert the measurements to mass flow rates.

Another point stressed prior to the time that experimentation begins concerns the water temperature. In discussing the impact that the water temperature will have on the overall process, the students are guided (the amount of guidance depends upon the student group) to create an experimental arrangement which can be most easily analyzed from a modeling point of view. The students are usually quite pleased with their decision to keep the water temperature at 0°C by adding ice to the water bath when they realize that not only did they create a situation in which temperature gradients within the liquid water surrounding the growing ice front do not have to be considered in their analysis, but also that energy input to the bath from the surroundings will not be a source of experimental error.

MODELING WORK TO GUIDE EXPERIMENTATION

During the very early stages of the project the students are required to begin their heat transfer analysis. Most of the students begin the lab course

with the idea that one first runs the experiment and then does the analysis, but our objective is to have them use their analytical capabilities to guide their experimental work and to have them design better experiments.

Figure 2 shows the physical characteristics of the heat transfer process to be analyzed. The tank which holds the dry ice/isopropanol mixture is made from brass and has an outside diameter of 68.3 cm and a height of 13.3 cm. Due to the highly agitated state of liquid isopropanol within the tank, the inside wall temperature may be safely assumed to be at the sublimation point of dry ice, -78.4°C . At the other heat transfer boundary, the advancing ice front will be at 0°C due to the addition of ice cubes to the liquid water bath. We have insulated the flat bottom and top of the tank with polyurethane foam in order to achieve only radial freezing and to avoid edge effects which are more difficult to analyze.

The important features of the analysis are as follows:

The heat flux at any time, q , is given as

$$q = h_b(2\pi r_1 L)(T_1 - T_b) = \frac{k_{br}(2\pi L)(T_2 - T_1)}{\ln(r_2/r_1)}$$

$$= \frac{k_{ice}(2\pi L)(T_0 - T_2)}{\ln(r_{ice}/r_2)}$$

In terms of the overall temperature difference

$$q = \frac{2\pi L(T_0 - T_b)}{\frac{1}{h_b r_1} + \frac{\ln r_2/r_1}{k_{br}} + \frac{\ln r_{ice}/r_2}{k_{ice}}}$$

Due to the large heat transfer coefficient of the highly agitated isopropanol and the high thermal conductivity of the brass relative to the ice, the flux may be written as (except as very short times)

$$q = \frac{2\pi L(T_0 - T_b)k_{ice}}{\ln(r_{ice}/r_2)} \quad (1)$$

Also implicit in Eq. (1) is the assumption of pseudo-steady conduction, *i.e.*, the characteristic conduction velocity (α/l_{ice}) in the ice is much greater than the velocity of the freezing front (v_{ice}). The validity of this assumption is to be checked against the data obtained.

Since all of the energy must come from the freezing of water at the ice front and the cooling off of the

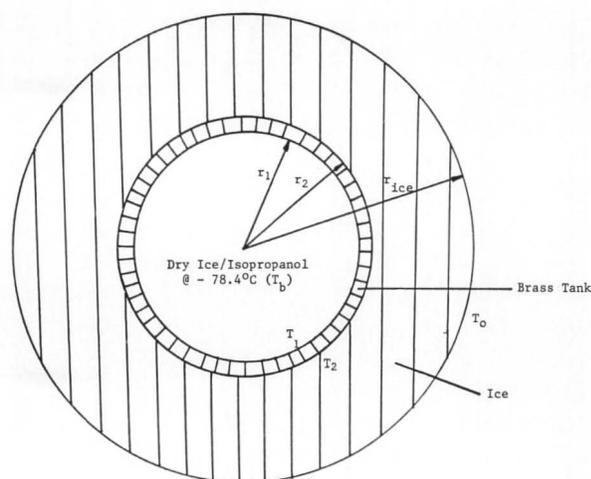


FIGURE 2. Radial view of tank and ice front

block of ice, the flux may also be written as

$$q = \frac{[\Delta H_f + C_p(T_0 - T_a)]dm_{ice}}{dt} \quad (2)$$

where ΔH_f is the heat of fusion of water, T_a is the average temperature within the ice and m_{ice} is the mass of ice. As an approximation to T_a we normally guide the students to take it as $T_a = (T_0 + T_b)/2$, or -39.2°C .

Since

$$m_{ice} = \pi(r_{ice}^2 - r_2^2)L\rho_{ice}$$

the combination of Eqs. (1) and (2) yields

$$\frac{[\Delta H_f + C_p(T_0 - T_a)]\rho_{ice} r_{ice} dr_{ice}}{dt} = \frac{(T_0 - T_b)k_{ice}}{\ln(r_{ice}/r_2)}$$

If C_p and k_{ice} are taken as constants evaluated at T_a , the integration may be carried out to yield

$$t = \frac{(\Delta H_f + C_p(T_0 - T_a))\rho_{ice}}{(T_0 - T_b)k_{ice}} \left(\frac{r_{ice}^2}{2} \left(\ln \left[\frac{r_{ice}}{2} \right] - \frac{1}{2} \right) + \frac{r_2^2}{4} \right) \quad (3)$$

This expression gives a straightforward relationship between the thickness of the ice and time.

We have found that the properties of ice at different temperatures are not as readily available as we at first assumed. Our recommendation is to use those values found in N. H. Fletcher's book, *The Chemical Physics of Ice* (Cambridge University Press, 1970). As such, we use

$$\Delta H_f \text{ (at } 0^{\circ}\text{C)} = 3.34 \times 10^5 \text{ J/kg}$$

$$C_p \text{ (at } T_a = -39.2^{\circ}\text{C)} = 1806 \text{ J/kg, } ^{\circ}\text{K}$$

$$k_{ice} \text{ (at } T_a = -39.2^{\circ}\text{C)} = 2.62 \text{ Watts/m, } ^{\circ}\text{K}$$

$$\rho_{ice} \text{ (at } T_a = -39.2^{\circ}\text{C)} = 920 \text{ kg/m}^3$$

As noted earlier, the measurement of the rate of sublimation of the dry ice allows the students to measure the actual heat flux, and by its comparison to the calculated heat flux (via Eq. (1)) to judge the goodness of the data. The actual flux (neglecting heat gain through the well-insulated top of the vessel) may be given as

$$q_{exp} = \dot{m}_{CO_2} \Delta H_{S,CO_2} = \dot{V}_{CO_2} \rho_{CO_2} \Delta H_{S,CO_2} \quad (4)$$

where \dot{V} is the volumetric flowrate of the sublimed dry ice, ρ_{CO_2} its density, and $\Delta H_{S,CO_2}$ is the heat of sublimation of CO_2 at one atmosphere. Although the CO_2 gas is certainly above its sublimation temperature by the time it passes through the wet test meter, the use of that temperature is not too bad an assumption (see next section) for calculating ρ_{CO_2} . In the future we plan to require the students to be more aware of the CO_2 temperature within the wet test meter to improve upon the accuracy of the heat flux measurement.

The usefulness of having the students work with the modeling during the early part of the project is that not only have they had to think very hard about the heat transfer process itself, but they gain firm ideas about the time frame of a good experiment, the eventual thickness of the ice formed during that time, and the evolution rate of gaseous CO_2 —especially at short times. We try very hard to get the students to use this information to guide them in carrying out good experiments.

EXPERIMENTAL WORK

In this project the experimental work is actually quite straightforward. With the water bath maintained at $0^\circ C$ by using ice cubes, the only real difficulty is associated with the very beginning of the experiment. The preferred situation is to have the dry ice/isopropanol mixture in the tank prior to the experiment and then to instantly place the tank in the water. There are some practical difficulties in accomplishing this, not the least of which is keeping frost from forming around the outside of the brass tank. Generally we have found that the easiest way to get the experiment started is to place the tank, containing only isopropanol, into the water bath and then to add the dry ice to the tank. This procedure requires a sacrifice of the early data for the sublimation rates and the radial movement of the ice front due to the necessity of cooling the isopropanol from about $0^\circ C$ to the dry ice temperature. However, this does happen fairly quickly and we find that it affects less than

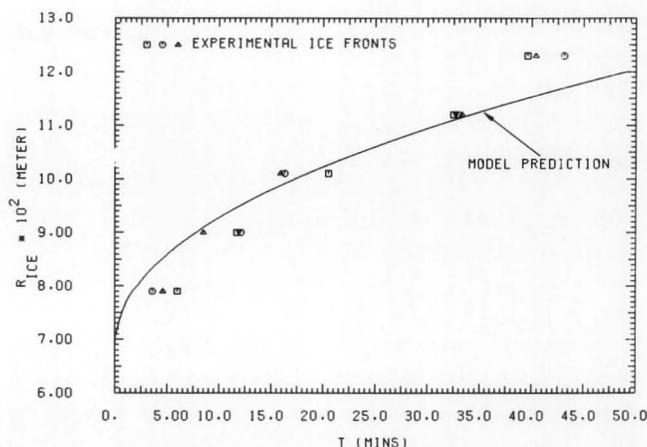


FIGURE 3. Radius of ice front vs. time

about 10% of the time generally required to carry out the experiment.

The students normally attach a plexiglass rod to the side of the tank which holds a measuring rule and to which can be attached a series of thermocouples. Without an attachment point for the thermocouples we have found that they tend to be displaced outward by the advancing ice front. Once the dry ice is introduced, data acquisition begins. The temperatures are continuously read off the thermocouples. The gas sublimation rate is also obtained with the help of the wet test meter. The ice front corresponds to an ice temperature of $0^\circ C$ and the time at which a thermocouple reading dips below $0^\circ C$ (corresponding to the ice front) is noted for the five equally-spaced thermocouples (2/5 in. apart). A typical run lasts about an hour during which the ice front would have advanced nearly two inches.

RESULTS AND DISCUSSION

We have chosen to present the experimental results of a recent student group studying this subject and judge these results to be about average for the various groups which have been involved in this project. The data represent a series of three experimental runs and, as such, give a view of typical experimental reproducibility.

Figure 3 shows the radial dimensions of the developing ice front (r_{ice}) as a function of time for three separate experiments. For comparison we have plotted the model predictions derived from Eq. (3). The goodness of the agreement between theory and experiment shown in Figure 3 is readily achieved by the students when they use the proper thermal conductivity of ice. In the earlier years of this project assignment, not enough attention was paid to obtaining a representative value for k_{ice} . With regard to the

pseudo-steady assumption made in Eq. (1) a typical calculation at $t = 20$ min in Figure 3 gives $v_{ice} = 1.39 \times 10^{-5}$ m/s, $l_{ice} = 3.43 \times 10^{-2}$ m, and $\alpha/l = 4.6 \times 10^{-5}$ m/s. Thus, this assumption is seen to be adequate at $t = 20$ min.

Figure 4 gives an indication of the difficulties of obtaining good values for the rate of CO_2 sublimation early in the experiment. The data scatter is easily

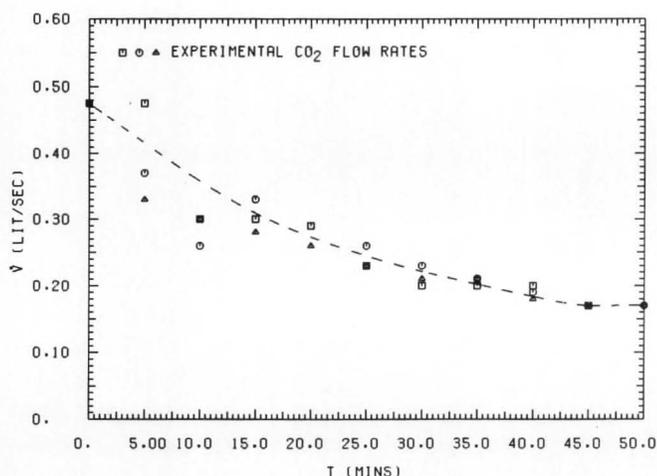


FIGURE 4. Carbon dioxide sublimation rate vs. time

$\pm 20\%$ during the first few minutes while the isopropanol is achieving its cold temperature and the ice buildup is small. As can be seen in the plot, the data scatter reduced considerably with increasing time. The dotted line in Figure 4 is simply a smooth curve fitted to the data. A number of points along this line are used to compute the average experimental heat flux via Eq. (4). In Figure 5 these experimental heat fluxes are compared with the predicted heat flux via Eqs. (1) and (3). Although the agreement between measured and predicted fluxes is not perfect over the entire time frame of the experiment, it does provide an adequate check upon the closure of the energy balance for a major portion of the experiment. In our view this is quite adequate for a junior level project of a relatively short time duration.

As an extension of the usefulness of the model developed and tested by the students, they are often asked to apply this model to a more realistic problem such as the one quoted in the assignment sheet described earlier. In this case, using representative values for the properties of soil with 10% moisture and LNG, they are then able to estimate the maximum extent to which the LNG will vaporize underground and the extent to which the surrounding soil will freeze during a reasonable time frame.

EVALUATION OF THE PROJECT

For the seven years we have conducted the laboratory course on an in-depth project basis we have found that about 80% of the students respond extremely favorably. They especially enjoy being able to dig into a problem in some detail and find it to be a welcome change from the more common lab course approach utilizing new experiments every week or two. The other 20% have some difficulty with the unstructured nature of such projects and would actually have preferred the more common approach, although in our view they would probably do about the same quality of work in either situation.

From the instructor's point of view the projects-oriented laboratory course is as gratifying as it is difficult to manage. We feel that projects such as those described in this paper give the instructor a real chance to teach the students how to apply what they are supposed to have learned in the classroom to a realistic situation, and to guide them to thoughtful and productive experimentation. This usually results in the students feeling more like engineers in control of the experiment rather than like technicians responding to a preset list of instructions. The difficulty for the instructor is often in managing ten or more simultaneous projects such as discussed here. Murphy's Law is a constant companion.

A particularly interesting and useful part of the project report is the oral presentation by each group. We have tried a variety of formats for this report including poster sessions and the seminar style of presentation. We have also utilized the video tape and/or color slides to allow the students to show their equipment and experiments while presenting their

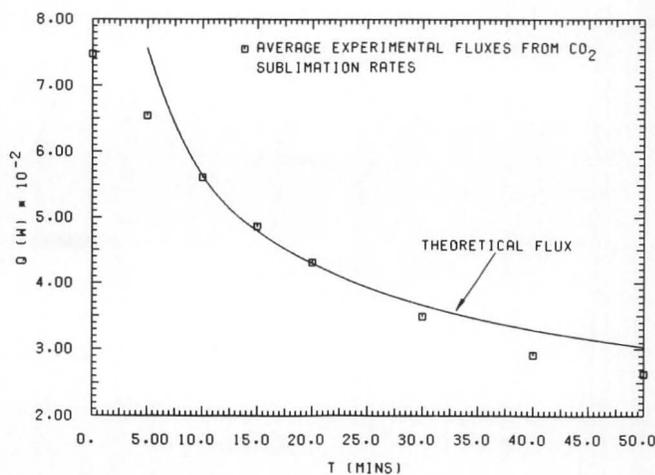


FIGURE 5. Comparison of heat flux from CO_2 sublimation data

seminar-style report in a conference room. A gratifying part of these presentations is the interest the other student groups show towards the various projects and the thoughtful questions that are asked during the discussion section of the presentations. In sum total, we feel that the overall experience is extremely beneficial to both the students and the instructors, and is definitely worth all of the work both parties have to do.

NOTATION

C_p	= heat capacity of ice (J/kg °K)
h_b	= boiling heat transfer coefficient (W/m ² °K)
L	= length of ice formation (m)
k	= thermal conductivity (W/m °K)
m	= mass of ice at time t (Kg)
\dot{m}	= mass flow rate of CO ₂ (Kg/s)
r	= radius described in Figure 2 (m)
q	= heat flux (W)
t	= time (s)
T	= temperature as described in Figure 2 (°K)
T_a	= average temperature of ice block (°K)
\dot{V}	= volumetric flow rate of sublimed dry ice (m ³ /s)
ρ	= density (Kg/m ³)
ΔH_f	= heat of fusion of ice (J/Kg)
ΔH_s	= heat of sublimation of CO ₂ (J/Kg) □

REVIEW: Reactor Design

Continued from page 31.

sively used in problem solving. This chapter introduces the concept of non-linear regression analysis and then illustrates it to the problem of kinetic parameter estimation.

Chapter 5 deals with the application of the concepts of earlier chapters to design and optimization. A number of case study examples are presented. The role of reactor design on selectivity is not discussed satisfactorily. Here an almost "Levenspielian" type of discussion would have been extremely beneficial from both a pedagogical and a practical point of view.

The coverage up to this point would probably fit nicely into a senior class in chemical reaction engineering. The instructor could assign a number of "end of chapter" problems in addition to assigning the case studies as computer simulation exercises. This would allow the students to get a fairly good grip on the use of modern computer based techniques.

The subsequent chapters cover more advanced topics. Chapter 6 discusses the laminar flow reactor, and this requires the solution of partial differential equation in two variables. The technique presented is a finite difference method. The chapter also discusses problems

involving variable viscosity, which are important in polymer processing. This chapter would blend in nicely for those students simultaneously taking a graduate level transport course.

The effect of non-idealities in the residence time is discussed in Chapter 7 where the axial dispersion model is discussed for both isothermal and non-isothermal reactions. The numerical solution strategy discussed here for the solution of the two point boundary value problem is the shooting method. The orthogonal collocation provides a more powerful solution method for these types of boundary value problems, but there is no mention of this method. A number of library packages such as COLSYS or PDE/PROTRAN could be directly used here, and it would have been useful to provide a brief exposure to the use of one or two commercially available software to reaction engineering problems.

Chapter 8 deals with unsteady state analysis of reactors. A number of examples are shown on the dynamics and control aspects. I found the examples both real and very illustrative.

Chapter 9 deals with the effect of mixing in continuous flow systems. In addition to providing the necessary mathematics, a valuable qualitative discussion on the mixing effects on reactor performance is presented. This should help the students to build a conceptual base. However, the Zwietering differential equation is introduced suddenly without any derivation or even a qualitative basis. More discussion here would have been useful.

Chapter 10 deals with heterogeneous catalysis, while Chapter 11 deals with multiphase reactors. Some applications to new processes such as biochemical reactors and electronic device fabrication are included. The treatment on three phase reactors is very sketchy. The emphasis on computer applications which was the theme in the first half of the book is unfortunately lacking here. For example, the author could have shown the use of single point collocation in the evaluation of effectiveness factors for nonlinear kinetics. A number of design problems in multiphase reactors can be solved by simple computer programs. (The *Omnibook* gives a rundown of typical examples.) These could have been useful.

The final chapter is exclusively devoted to polymer reaction engineering, which is unique since many books do not even mention this word.

The second part of the book (Chapters 9 through 11) provides sufficient content for a graduate course, although the instructor would have to supplement the text with additional reading materials or notes to provide further details on many of the topics. The coverage of emerging areas would be useful in such a course, and the book would motivate the students to read more on those topics. The incorporation of the computer methods in the teaching of reaction engineering is vital, and the book provides a valuable reference source in this field. □

LUBRICATION FLOWS

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LUBRICATION FLOWS ARE perhaps the most applicable material of fluid mechanics at both the undergraduate and the graduate levels. At the undergraduate level, important one-dimensional approximations such as channel, film, and coating flow equations can be derived and studied from simplified mass and momentum balances by means of the control volume principle or else by simplifying the general equations of change (Navier-Stokes). This leads to the celebrated Reynolds equation [1]

$$R(h, p, Ca) = 0 \quad (1)$$

where h is the thickness of the narrow channel or of the thin film, p is a generalized pressure, $p = P - St g$ where $St = \rho g D^2 / \mu V$ is the Stokes number and g the gravity acceleration in the direction of fluid motion. The capillary number, $Ca = \mu V / \sigma$, usually enters



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through the balance of the normal stresses at a free surface.

Eq. (1) can be solved:

- To find the pressure distribution and relative quantities (load capacity, friction and wear, cavitation, etc) when the thickness $h(x)$ is known. The most typical application is journal-bearing lubrications.
- To find the thickness $h(x)$ when the pressure is known. The most typical applications are formation of thin films and coating applications.

Eq. (1) is not always solvable analytically. In some extreme cases it is solvable by simplified perturbation techniques. By the time the student reaches the solution, he/she must have dealt with

- Derivation of governing differential equations by mass and momentum balances on appropriately chosen control volumes (or alternatively, the Navier-Stokes equations).
- Order of magnitude analysis to derive the lubrication equations.
- The solution of the differential lubrication equations subject to boundary conditions, to find the velocity profile.
- The integral mass conservation equation to derive the Reynolds equation.
- The surface tension and the curvature of a thin film, to find the pressure distribution.
- The solution of the Reynolds equation, to find the film thickness or the pressure distribution.
- Simplified perturbation techniques to find limiting solutions to the Reynolds equation.

Thus, lubrication flows cover most of the material taught in undergraduate fluid mechanics and at the same time are attractive to the student because they deal with practical problems.

The most important applications of the thin film lubrication equations are films falling under surface tension, nonisothermal films, dip and extrusion coating, and wetting and liquid spreading. A similar class of problems includes centrifugal spreading, common in bell sprayers and in spin coating.

INTRODUCTION

The lubrication approximation for flows in *nearly* rectilinear channels or pipes, of *nearly* parallel walls, can be derived intuitively from the equations of flow in rectilinear channels and pipes. The equations that govern flows in rectilinear channels and pipes are the continuity or mass conservation which demands constant flow rate

$$\frac{\partial u_x}{\partial x} = 0; \quad u_z = 0; \quad u_x = f(z) \quad (2)$$

and the equation of conservation of linear momentum in the flow direction

$$\frac{dP}{dx} = \mu \frac{\partial^2 u_x}{\partial z^2} \quad (3)$$

which under constant pressure gradient, dP/dx , predicts linear shear stress and parabolic velocity profiles. The gradient, dP/dx , is usually imposed mechanically, and, since the channel is rectilinear and the mo-

tion steady, it is constant along the channel (see Figure 1a), equal to $\Delta P/\Delta L$, where ΔP is the pressure difference over distance ΔL . Thus, the mechanism of motion is simple; flow of material from regions of high pressure to regions of low pressure. This is Poiseuille flow.

When one or both walls are in slight inclination, α , to the midplane of symmetry, the same governing equations are expected to hold which may now be locally weak functions of x , of order α . The most obvious difference is the pressure gradient, dP/dx . In the case of a lubrication flow which may be accelerating or decelerating, in a converging or diverging channel, respectively, dP/dx is not constant along the channel because the pressure forces needed to move two cones of liquid of the same height dx at two different positions along the channel are different (see Figure 1b). Thus, dP/dx is a function of x and so is the velocity in the governing equations

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} = 0 \quad (4)$$

$$\frac{dP(x)}{dx} = \mu \frac{\partial^2 u_x}{\partial z^2} \quad (5)$$

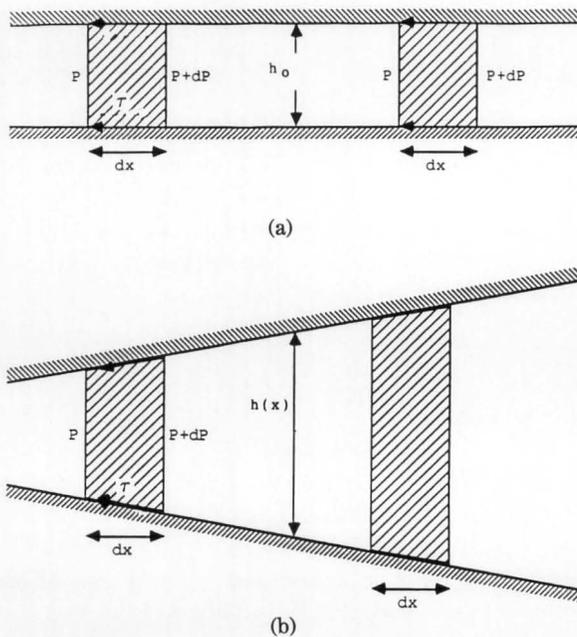


FIGURE 1. Force balance in a rectilinear flow, $h_0 dP = 2\tau dx$, and in lubrication flow, $h(x) dP(x) = 2\tau(x)dx$.

Both Eqs. (3) and (5) express conservation of linear momentum or the Newton's law of motion that there is no accumulation of momentum in a control volume because there is no substantial net convection, and the forces capable of producing momentum are in equilibrium. According to Newton's law of motion there is no acceleration (actually the acceleration is vanishingly small in lubrication flows) because there is no net force acting on a control volume. The forces on the control volume, of height Δx , are net pressure force $(dP/dx)A(x)$ and shear stress force $A(x)dx\tau_{xy}$ (Figure 1b). The underlying mechanism is more complex than in the Poiseuille flow. First, the moving wall on one side sweeps fluid into a narrowing passage through the action of viscous shear forces, which gives rise to a local velocity profile of Couette-type $u_x = Vy/h$, with flow rate, $Q = Vh/2$. Because Q is constant by continuity and $h(x)$ is diminishing, the flow sets up a pressure gradient to supply a Poiseuille component

that redistributes the fluid and maintains a constant flow rate (Figure 2).

Derivation of Lubrication Equations by the Navier-Stokes Equations

Alternatively, the lubrication equation can be derived by order of magnitude and dimensionless analysis of the full, two-dimensional, Navier-Stokes equations

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} = 0$$

$$\rho \left[\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_z \frac{\partial u_x}{\partial z} \right] = - \frac{\partial P}{\partial x} + \mu \left[\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial z^2} \right] \quad (6)$$

$$\rho \left[\frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_z \frac{\partial u_z}{\partial z} \right] = - \frac{\partial P}{\partial z} + \mu \left[\frac{\partial^2 u_z}{\partial z^2} + \frac{\partial^2 u_z}{\partial x^2} \right] \quad (7)$$

where x is the direction of flow and z the gapwise direction. The geometry of the flow is shown in Figure 2.

There are several good reasons to work with dimensionless equations and variables: to reduce the dependence of the solution to minimum dimensionless numbers; to simplify the equations judging from the relative magnitude of a dimensionless number to one; and to scale-up experiments to real applications of the same dimensionless number.

To achieve these goals

- The dimensionless variable, say u^* , must be of the order of one. By using the boundary velocity V , then $u_x^* = u_x/V$ may at most vary between zero and one, and so u^* is of order one.
- If the problem lacks the characteristic dimensional variable, V , in the previous paragraph, then it is made-up by combining other characteristic variables. For example, for time, $t^* = t/(L/V)$. The characteristic dimensional variable for pressure is $P = \mu V/\alpha L$, because viscous forces, which resist the motion, are in equilibrium with the pressure forces, as shown by Figure 1.

Accordingly, define

$$x^* = \frac{x}{L}; \quad z^* = \frac{z}{\alpha L}; \quad t^* = \frac{tV}{L}; \quad h^* = \frac{h}{\alpha L};$$

$$u_x^* = \frac{u_x}{V}; \quad u_z^* = \frac{u_z}{\alpha V}; \quad P^* = \frac{P}{\mu \frac{V}{\alpha^2 L}}; \quad (8)$$

which upon substitution in the N-S equations, yields

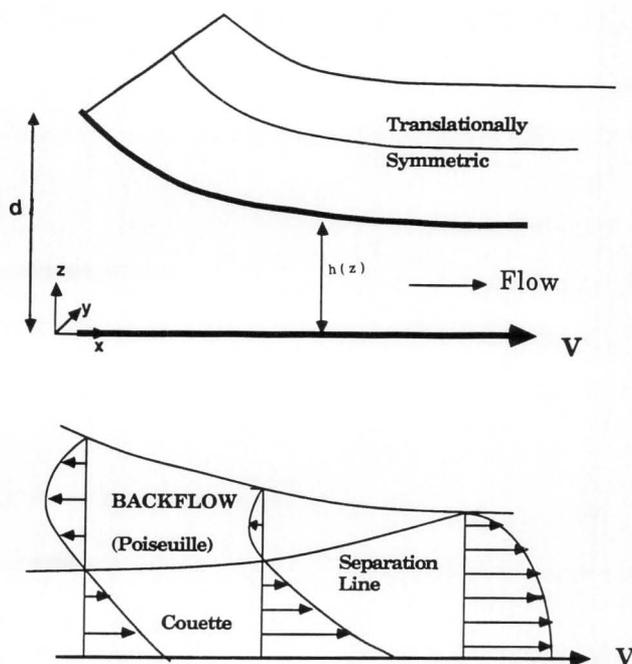


FIGURE 2. Geometry of a two-dimensional lubrication flow. The velocity profiles along the channel are mixtures of Couette and Poiseuille.

(with asterisk suppressed hereafter)

$$\alpha \text{Re} \left(\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_z \frac{\partial u_x}{\partial z} \right) = \left(- \frac{\partial P}{\partial x} + \alpha^2 \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial z^2} \right) \quad (9)$$

$$\alpha^3 \text{Re} \left(\frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_z \frac{\partial u_z}{\partial z} \right) = \left(- \frac{\partial P}{\partial z} + \alpha^4 \frac{\partial^2 u_z}{\partial x^2} + \alpha^2 \frac{\partial^2 u_z}{\partial z^2} \right) \quad (10)$$

The lubrication equation holds in geometries where $\alpha \ll 1$. Since all the dimensionless terms and derivatives in these two equations are of order one, the resulting lubrication dimensionless equations are in the limit of $\alpha = 0$ and $\alpha \text{Re} = 0$,

$$- \frac{\partial P}{\partial x} + \frac{\partial^2 u_x}{\partial z^2} = 0 \quad (11)$$

$$- \frac{\partial P}{\partial z} = 0 \quad (12)$$

These equations are similar to those derived intuitively from channel flow [e.g., Eqs. (2) and (3)]. Notice that high Reynolds numbers are allowed as far as the product αRe is vanishingly small and the flow remains laminar.

The appropriate boundary conditions to Eqs. (5) and (11) are

At $z = 0$, $u_x = V$ (no-slip boundary condition)
 At $z = h$, $u_x = 0$ (Slit Flow), (no slip boundary condition)
 or $z = h$, $\tau_{zx} = 0$ (Thin Film), (zero shear stress at free surface)

Under these conditions the solution to Eq. (5) is

$$u_x = -\frac{1}{2\mu} \frac{dP}{dx} (zh - z^2) + V - \frac{z}{h} V \quad (\text{Slit Flow}) \quad (13)$$

$$u_x = -\frac{1}{2\mu} \frac{dP}{dx} (2zh - z^2) + V \quad (\text{Film Flow}) \quad (14)$$

The volume flux and the pressure distribution in the lubricant layer can be calculated when the flow rate Q , and the inclination α , are known. A lubrication layer will generate a positive pressure and thus load capacity, normal to this layer, only when the layer is so arranged that the relative motion of the two surfaces tends to drag fluid by viscous stresses from the wider to the narrower end of the layer [2]. The load, W , supported by the pressure is

$$W = \int_0^L (P - P_0) dx = \frac{6\mu V}{\alpha^2} \left[\log \frac{d}{d - \alpha L} - 2 \left(\frac{\alpha L}{2d - \alpha L} \right) \right] \quad (15)$$

Thus, the inclination α , is responsible for the pressure build-up by decelerating the flow and transmitting momentum and thus load capacity to the upper boundary.

Reynolds Equation for Lubrication

Mass conservation on an infinitesimal volume yields

$$-Q_{x+dx} + Q_x = dx \frac{dh}{dt} \quad (16)$$

which states that the net mass convection in the control volume is being used to increase the volume at rate d/dt ($dx dh$) where dx and dh are the width in the flow direction and the height of the volume, respectively. Rearrangement yields

$$-\frac{dQ}{dx} = \frac{dh}{dt} \quad (17)$$

which for confined and film flows reduces to

$$\frac{d}{dx} \left[-\frac{1}{2\mu} \frac{dP}{dx} \frac{h^3}{6} + \frac{hV}{2} \right] = -\frac{dh}{dt} \quad (\text{Slit Flow}) \quad (18)$$

and

$$\frac{d}{dx} \left[-\frac{1}{\mu} \frac{dP}{dx} \frac{h^3}{3} + hV \right] = -\frac{dh}{dt} \quad (\text{Film Flow}) \quad (19)$$

respectively.

Solution of Steady Reynolds Equation for Slit Flow

The steady-state form of Eq. (18)

$$\frac{d}{dx} \left[-\frac{1}{2\mu} \frac{dP}{dx} \frac{h^3}{6} + \frac{hV}{2} \right] = 0$$

is integrated to

$$-\frac{1}{2\mu} \frac{dP}{dx} \frac{h^3}{6} + \frac{hV}{2} = Q$$

and one proceeds according to Batchelor [2] and Denn [3] to the calculation of pressure

$$P(x) = P_0 + 6\mu V \int_0^x \frac{dx}{h^2(x)} - 12\mu Q \int_0^x \frac{dx}{h^3(x)} \quad (19a)$$

where

$$Q = \frac{P_0 - P_L}{12\mu \int_0^L \frac{1}{h^3(x)} dx} + \frac{V}{2} \frac{\int_0^L \frac{1}{h^2(x)} dx}{\int_0^L \frac{1}{h^3(x)} dx} \quad (19b)$$

Then one can proceed to the evaluation of load capacity

$$W = \int_s [P_0 - P(x)] ds \quad (19c)$$

and of shear or friction

$$F = \int_s \tau_{zx} ds \quad (19d)$$

on the surface, S . It is easy to show that the load capacity is of order α^{-2} whereas the shear or friction is of order α^{-1} . Thus the ratio load/friction increases with α^{-1} .

The most important application of the lubrication theory for confined flows in journal-bearing [4] and piston-ring [5] systems of engines. Other flows that can be studied at the undergraduate level by means of the lubrication equations, include wire coating [3], forward roll coating [6], and many polymer applications [7]. The solution to these problems follows the procedure outlined above, starting from Eq. (17). The flow rate is usually given by

$$Q = V h_f \quad (20)$$

where V is the speed of production and h_f the final thickness. The boundary condition on the pressure at the outlet may vary [8]. $P(L)=0$, $dP(L)/dx=0$, or $P(L)=2/(h_f)^2$.

Solution of Steady, Reynolds Equations for Film Flow

In confined lubrication flows there is pressure build-up due to inclination, α , and backflow of some of the entering liquid. The pressure is then usefully used to support loads. In thin film lubrication flows, any pressure build-up is due to surface tension, and in fact if the surface tension is negligible the pressure gradient is zero.

The steady-state form of Eq. (19)

$$\frac{d}{dx} \left[-\frac{1}{\mu} \frac{dP}{dx} \frac{h^3}{3} + Vh \right] = 0$$

is integrated to

$$-\frac{1}{\mu} \frac{dP}{dx} \frac{h^3}{3} + Vh = Q = Vh_f \quad (21)$$

The film thickness, h , is not known. However, the pressure drop, dP/dx , can be deduced from the surface tension by means of the Young-Laplace equation under the lubrication requirement that the slope, dh/dx , must be much less than unity

$$-P = \frac{\sigma \frac{d^2 h}{dx^2}}{\left[1 + \left(\frac{dh}{dx} \right)^2 \right]^{\frac{1}{2}}} \approx \sigma \frac{d^2 h}{dx^2} \quad (22)$$

Here $h(x)$ is the elevation of the free surface from the x -axis, and σ the surface tension of the liquid. Then

$$-\frac{dP}{dx} = \sigma \frac{d^3 h}{dx^3} \quad (23)$$

and substitution of dP/dx in Eq. (21) yields

$$\frac{\sigma}{\mu} \frac{h^3}{3} \frac{d^3 h}{dx^3} + hV = Vh_f \quad (24)$$

which is rearranged to

$$h^3 \frac{d^3 h}{dx^3} + 3 Ca (h - h_f) = 0 \quad (25)$$

The capillary number $Ca = \mu V / \sigma$ is another dimensionless number and measures the viscous to surface tension forces. Eq. (24) is highly nonlinear and cannot be solved analytically.

The most important applications of the thin film lubrication equations are films falling under surface tension, nonisothermal films, dip and extrusion coating, and wetting and liquid spreading. A similar class of problems includes centrifugal spreading, common in bell sprayers and in spin coating. A rich collection of lubrication problems from polymer processing can be found in Pearson [7, 9] and from coating in several theses under Scriven [10].

CONCLUSIONS

Lubrication flows are ideal for undergraduate students to cover and learn a significant amount of fluid mechanics material. This material includes the differential Navier-Stokes equations, dimensional analysis and simplified dimensionless numbers, control volume principles, the Reynolds lubrication equation for confined and free surface flows, capillary pressure, and simplified perturbation techniques. Problems and solutions can be easily chosen from practical and interesting applications such as journal bearing, expanding pipe flow, film flow, and several polymer and coating operations.

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APPENDIX

Vertical Dip Coating

An example of thin lubrication film under gravity, surface tension, and viscous drag arises in dip coating, shown in Figure 3. This method of coating is practiced to cover metals with anticorrosion layers and to laminate paper and polymer films. The substrate is being withdrawn at speed V from a liquid bath of density ρ , viscosity μ , and surface tension σ . The analysis will predict the final coating thickness as a function of the processing conditions (withdrawal speed) and of the physical characteristics of the liquid (ρ , μ , and σ).

Solution

The governing momentum equation, with respect to the shown cartesian system of coordinates is

$$-\frac{dP}{dz} + \mu \frac{\partial^2 u_z}{\partial y^2} - \rho g = 0 \quad (A1)$$

The boundary conditions are

$$u_z(y=0) = V \quad (A2)$$

and

$$\tau_{zy}(y=H) = \mu \frac{du_z}{dy} = 0 \quad (A3)$$

The particular solution is

$$u_z = \frac{1}{\mu} \left(\frac{dP}{dz} + \rho g \right) \left(\frac{y^2}{2} - Hy \right) + V \quad (A4)$$

The resulting Reynolds equation is

$$-\frac{1}{\mu} \left(\frac{dP}{dz} + \rho g \right) \frac{H^3}{3} + VH = Q = VH_f \quad (A5)$$

where H_f is the final coating thickness.

The pressure gradient

$$\frac{dP}{dz} = -\sigma \frac{d^3 H}{dz^3} \quad (A6)$$

is replaced in Eq. (A5) to yield the final Reynolds equation

$$\frac{1}{\mu} \left(\sigma \frac{d^3 H}{dz^3} - \rho g \right) \frac{H^3}{3} + V(H - H_f) = 0 \quad (A7)$$

which is rearranged to the form

$$\frac{H^3}{3} \frac{d^3 H}{dz^3} - \frac{\rho g}{\sigma} \frac{H^3}{3} + \frac{V\mu}{\sigma} (H - H_f) = 0 \quad (A8)$$

By identifying the dimensionless numbers

$$Ca = \frac{V\mu}{\sigma} \quad (A9)$$

and

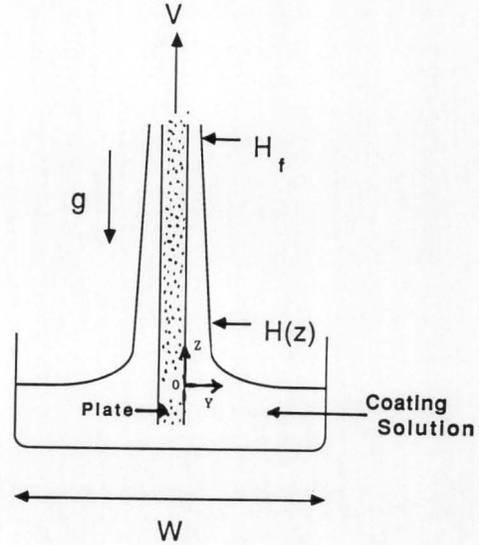


FIGURE 3. Dip Coating: A coated plate is being withdrawn from a coating solution. A final thin film or coating results on the plate under the combined action of gravity, surface tension, and drag by the moving substrate.

$$St = \frac{\rho g H_f^2}{\mu V} \quad (A10)$$

Eq.(A8) becomes

$$\frac{H^3}{Ca} \frac{d^3 H}{dz^3} - St \frac{H^3}{H_f^2} + 3(H - H_f) = 0 \quad (A11)$$

which can be solved directly for the following limiting cases:

1. Negligible surface tension ($Ca \rightarrow \infty$)

Eq. (A11) reduces to the third-order algebraic equation

$$H^3 - \frac{3H_f^2}{St} H + \frac{3H_f^3}{St} = 0 \quad (A12)$$

In the limit of infinite St (i.e., very heavy liquid!), the only solution is $H = 0$, i.e., no coating. In the limit of zero St (i.e., horizontal arrangement), $H = H_f$, i.e., plain Couette (plug) flow. For finite values of St the solution is independent of z , which predicts a flat film throughout.

2. Infinitely large surface tension ($Ca \rightarrow 0$)

Eq. (A10) reduces to

$$\frac{d^3 H}{dz^3} = 0 \quad (A13)$$

with general solution

$$H(z) = C_1 \frac{z^2}{2} + C_2 z + C_3 \quad (A14)$$

along with the boundary conditions

$$H(z=0) = W/2, \quad H(z=L) = H_f, \quad (dH/dz)_{z=L} = 0$$

The solution is

$$H(z) = \left(\frac{W - 2H_f}{L^2} \right) \left(\frac{z^2}{2} - zL \right) + \frac{W}{2} \quad (\text{A15})$$

which is a parabolic film thickness.

3. Finite surface tension ($0 < Ca < k$)

Eq. (A11) is cast in the form

$$H^3 \left(\frac{d^3 H}{dz^3} - \frac{St \cdot Ca}{H_f^2} \right) + 3Ca(H - H_f) = 0 \quad (\text{A16})$$

with no apparent analytic solution. For a special case of horizontal coating ($St = 0$), and since usually $H_f / W \ll 1$, the transformation

$$H^* = \frac{H}{W}, \quad z^* = \frac{z}{W} \quad (\text{A17})$$

reduces Eq. (A16) to

$$H^{*3} \frac{d^3 H^*}{dz^{*3}} + 3Ca \left(H^* - \frac{H_f}{W} \right) = 0 \quad (\text{A18})$$

which predicts that near the inlet, where $H^* \approx 1$, the film decays with rate depending on the Ca . Near the other end, where $H^* \approx 2H_f/W$, the film becomes flat, surface tension becomes unimportant, and therefore the slope is zero. Eq. (A18) can be solved asymptotically by perturbation techniques. \square

CHEATING

Continued from page 17.

this paper. Perhaps these considerations will motivate us to develop innovative ethics curricula and to improve monitoring of course activities, so that our disciplines may be able to better safeguard (and perhaps even increase) their already high levels of excellence.

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Auburn University	Lehigh University	Rose-Hulman Institute of Technology
Brigham Young University	Loughborough University of Technology	Rutgers University
University of British Columbia	Louisiana State University	University of Saskatchewan
Brown University	Louisiana Technical University	University of Sherbrooke
Bucknell University	University of Louisville	University of South Alabama
California Institute of Technology	University of Lowell	University of South Carolina
California State Polytechnic University	University of Maine	South Dakota School of Mines
California State University, Long Beach	Manhattan College	University of South Florida
University of California (Berkeley)	University of Maryland	University of Southern California
University of California (Davis)	Massachusetts Institute of Technology	University of Southwestern Louisiana
University of California (Los Angeles)	McGill University	Stanford University
University of California (Santa Barbara)	McMaster University	Stevens Institute of Technology
University of California at San Diego	Michigan Technical University	University of Sydney
Carnegie-Mellon University	University of Missouri (Columbia)	Syracuse University
Case-Western Reserve University	University of Missouri (Rolla)	Teesside Polytechnic Inst.
University of Cincinnati	Monash University	Tennessee Technological University
Clarkson University	Montana State University	University of Tennessee
Clemson University	University of Nebraska	Texas A&M University
Cleveland State University	University of New Hampshire	University of Texas at Austin
University of Colorado	University of New Haven	Texas Technological University
Colorado School of Mines	New Jersey Institute of Tech.	University of Toledo
Colorado State University	University of New Mexico	Tri-State University
Columbia University	New Mexico State University	Tufts University
University of Connecticut	University of New South Wales	University of Tulsa
Cornell University	Polytechnic Institute of New York	Tuskegee Institute
Dartmouth College	State University of N.Y. at Buffalo	University of Utah
University of Dayton	North Carolina A&T State University	Vanderbilt University
University of Delaware	North Carolina State University	Villanova University
Drexel University	University of North Dakota	University of Virginia
University of Florida	Northeastern University	Virginia Polytechnic Institute
Florida State University	Northwestern University	Washington State University
Florida Institute of Technology	University of Notre Dame	University of Washington
Georgia Institute of Technology	Nova Scotia Technical College	Washington University
University of Houston	Ohio University	University of Waterloo
Howard University	University of Oklahoma	Wayne State University
University of Idaho	Oklahoma State University	West Virginia College of Grad Studies
University of Illinois (Chicago)	Oregon State University	West Virginia Institute Technology
University of Illinois (Urbana)	University of Ottawa	West Virginia University
Illinois Institute of Technology	University of Pennsylvania	Widener University
University of Iowa	Pennsylvania State University	University of Wisconsin (Madison)
Iowa State University	University of Pittsburgh	Worcester Polytechnic Institute
Johns Hopkins University	Princeton University	University of Wyoming
University of Kansas	Purdue University	Yale University
Kansas State University	Queen's University	Youngstown State University

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