

# CHE

## chemical engineering education

VOLUME XII

NUMBER 1

WINTER 1978

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

### Teaching Process Design With A Business Game

RUSSELL & FRANKEL

### Efficiencies In Separation Processes

DRINKENBURG

### ChEs Look At Materials Education

GRISKEY

### Take Two Pills Every Four Hours

JACKSON & STEVENSON

### Telephone Tutorial Service

HIMMELBLAU

### Thermodynamic Heresies

SUSSMAN

### Population Balances

RAMKRISHNA

### The Road To Hell

ZIPF

## ChE at Penn State

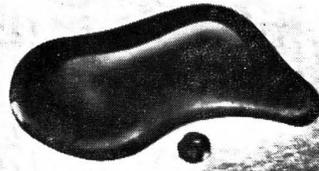
### Scott Fogler

of U. of Michigan



ALSO: Summer School At Snowmass

# YOU SEE OIL.



# UNION CARBIDE SEES MORE...

*Most oil and natural gas are burned as fuel. About 4% become petrochemical products—synthetic fabrics, paints, plastics, even medicines. Another product is jobs. There are 11 million petrochemical-related jobs in the United States.*



## **THE MOST VERSATILE RAW MATERIAL ON EARTH.**

Through heat and cold, pressure and vacuum, we transform petroleum molecules into the man-made resources that will build a better life for more of the world's people.

## **BRIGHT FUTURES.**

Millions of pounds of Union Carbide ingredients — solvents, resins and latexes — help modern paints protect and beautify just about everything under the sun. And rain.

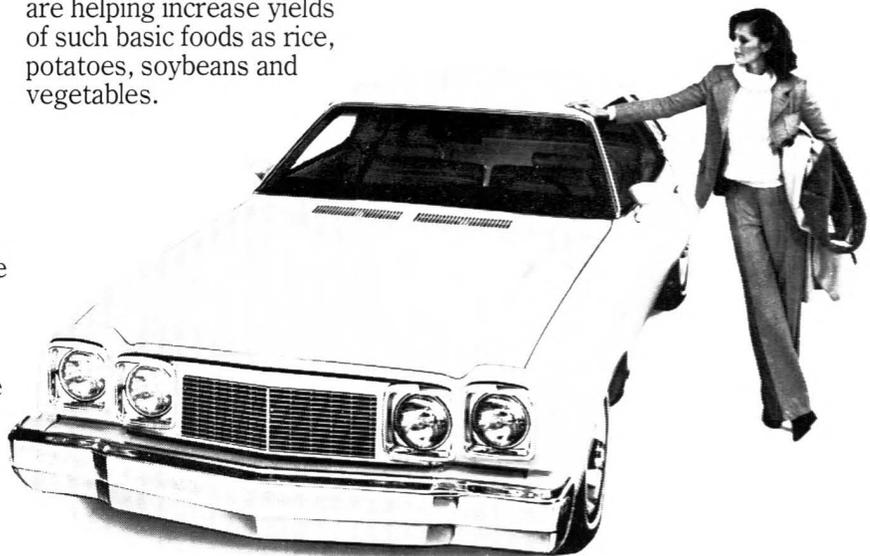


## **PESTICIDES TO HELP FEED THE WORLD.**

To feed the world's growing population, we need to stop the insects that compete with us for food. Around the world, Union Carbide's pesticides are helping increase yields of such basic foods as rice, potatoes, soybeans and vegetables.

## **CARS THAT SAVE GAS. FABRICS THAT SAVE BOTHER.**

Plastics will increasingly replace heavier metal parts as auto makers strive for better gas mileage. But Union Carbide is already helping auto makers, with petrochemicals for everything from light urethane bumpers to polyethylene electrical insulation. We even make Prestone II<sup>®</sup> anti-freeze. Your carefree synthetic fabrics are petrochemicals, too. Union Carbide makes the basic ingredient in polyester, the most popular synthetic of all.



**WORKING WITH NATURE TODAY,  
FOR THE RESOURCES WE'LL NEED TOMORROW.**

Union Carbide Corporation, 270 Park Avenue, New York, N.Y. 10017

# Chemical Engineering Education

VOLUME XII

NUMBER 1

WINTER 1978

## EDITORIAL AND BUSINESS ADDRESS

Department of Chemical Engineering  
University of Florida  
Gainesville, Florida 32611

Editor: *Ray Fahien*

Associate Editor: *Mack Tyner*

Business Manager: *R. B. Bennett*

Managing Editor: *Bonnie Neelands*  
(904) 392-0861

## Publications Board and Regional Advertising Representatives:

### Chairman:

*Darsh T. Wasan*  
Illinois Institute of Technology

### SOUTH:

*Homer F. Johnson*  
University of Tennessee

*Vincent W. Uhl*  
University of Virginia

CENTRAL: *Lestlie E. Lahti*  
University of Toledo

*Camden A. Coberly*  
University of Wisconsin

WEST: *George F. Meenaghan*  
Texas Tech University

*William H. Corcoran*  
California Institute of Technology

*William B. Krantz*  
University of Colorado

EAST: *Thomas W. Weber*  
State University of New York

*Lee C. Eagleton*  
Pennsylvania State University

NORTH: *J. J. Martin*  
University of Michigan

*Edward B. Stuart*  
University of Pittsburgh

NORTHWEST: *R. W. Moulton*  
University of Washington

*Charles E. Wicks*  
Oregon State University

PUBLISHERS REPRESENTATIVE  
*D. R. Coughanour*  
Drexel University

UNIVERSITY REPRESENTATIVE  
*Stuart W. Churchill*  
University of Pennsylvania

## FEATURES

- 26 A Telephone Tutorial Service,  
*D. Himmelblau*
- 33 The Road to Hell,  
*K. Zipf*

## DEPARTMENTS

### 4 The Educator

Scott Fogler of the University of Michigan

### 8 Departments of Chemical Engineering

Penn State

### 14 Lecture

The Prospects of Population Balances,  
*D. Ramkrishna*

### 18 Classroom

Teaching the Basic Elements of Process  
Design with a Business Game,  
*T. Russell and D. Frankel*

### 30 Laboratory

Take Two Pills Every Four Hours: Hydrody-  
namic Analog for Drug Dosage Regimens,  
*S. Jackson and J. Stevenson*

### 34 Views and Opinions

Thermodynamic Heresies, *M. Sussman*

### 38 International

Use and Abuse of Efficiencies in Separation  
Processes, *A. Drinkenburg*

### 44 Curriculum

What Does the Practicing ChE Want in  
Materials Education, *R. Grisley*

### 3 Division Activities

### 43, 47 Letters

### 23, 37, 46 Book Reviews

CHEMICAL ENGINEERING EDUCATION is published quarterly by the Chemical Engineering Division, American Society for Engineering Education. The publication is edited at the Chemical Engineering Department, University of Florida. Second-class postage is paid at Gainesville, Florida, and at DeLeon Springs, Florida. Correspondence regarding editorial matter, circulation and changes of address should be addressed to the Editor at Gainesville, Florida 32611. Advertising rates and information are available from the advertising representatives. Plates and other advertising material may be sent directly to the printer: E. O. Painter Printing Co., P. O. Box 877, DeLeon Springs, Florida 32028. Subscription rate U.S., Canada, and Mexico is \$10 per year, \$7 per year mailed to members of AIChE and of the ChE Division of ASEE. Bulk subscription rates to ChE faculty on request. Write for prices on individual back copies. Copyright © 1978 Chemical Engineering Division of American Society for Engineering Education, Ray Fahien, Editor. The statements and opinions expressed in this periodical are those of the writers and not necessarily those of the ChE Division of the ASEE which body assumes no responsibility for them. Defective copies replaced if notified within 120 days.

The International Organization for Standardization has assigned the code US ISSN 0009-2479 for the identification of this periodical.

# "At DuPont you don't get lost in a big company atmosphere. It's very personal."

—George D. Peterson BS, Chemical Engineering



"Du Pont is a big company but it's broken down into satellites. So you don't get lost in a big-company atmosphere. It's very personal, and I think the people are top-notch.

"I started in technical here at the Belle Plant in West Virginia. Now I'm a production supervisor. Production is solving problems on a day-to-day basis. I like working under that kind of pressure. When things

work out, it's very rewarding. So is working with people. I'm responsible for helping 22 people do their jobs."

George was recruited by Du Pont from the Michigan Technological University campus in 1973. He interviewed about 25 companies.

George's story is typical of many Chemical, Mechanical and Electrical Engineers who've chosen careers at Du Pont.

We place no limits on the progress our engineers can make. And we place no limits on the contribution they can make—to themselves, the Company or to society.

If this sounds like your kind of company, do what George Peterson did. Talk to the Du Pont representative who visits your campus. Or write: Du Pont Company, Room 35972, Wilmington, DE 19898.

At Du Pont...there's a world of things YOU can do something about.



An Equal Opportunity Employer, M/F



## SUMMER SCHOOL IN SNOWMASS

C. JUDSON KING  
*University of California  
Berkeley, California 94720*

**T**HE PENTENNIAL Summer School for Chemical Engineering Faculty was held in Snowmass Colorado—July 31-August 5, 1977. There were 270 professional attendees. Many brought their families, so that there were over 700 persons in Snowmass connected with the Summer School.

Financial support was contributed by thirty industrial companies and two foundations; donors are shown in the Table. This covered expenses for workshop leaders, travel and meal/lodging subsidy for participants and both a group dinner and a group barbecue. There were 37 attendees present from industry. This contributed positively in many ways.

The program of the Summer School was built to a large extent around new applications of chemical engineering. There were sessions on biochemical engineering, food processing, metallurgical processing, a novel approach to industrial chemistry, electrochemical engineering, surface and colloid phenomena, and technology assessment. Other popular topics included kinetics and reactor design, the structure of the chemical process industries, process economics, novel teaching methods, uses of interactive computing, and various administrative questions.

Colorado proved to be hospitable in many ways, including the weather (until the last day!). Participants got to know Aspen and explored many scenic hiking trails in the vicinity during free afternoons.

The Organizing Committee for the 1977 Summer School consisted of Mike Williams and Jud King (Berkeley)—Co-Chairmen; Peter Clark (Virginia Poly); Stan Barnett (Rhode Island);

Alex Bell (Berkeley); Fraser Russell (Delaware); Don Woods (McMaster); Ernie Henley (Houston); and John Prados (Tennessee). The next Summer School, probably to be held in 1982, will be organized by Fraser Russell of the University of Delaware. He will welcome comments and suggestions. □

**TABLE 1.**  
**Sponsors of 1977 Summer School for Chemical Engineering Faculty**

**Companies:**

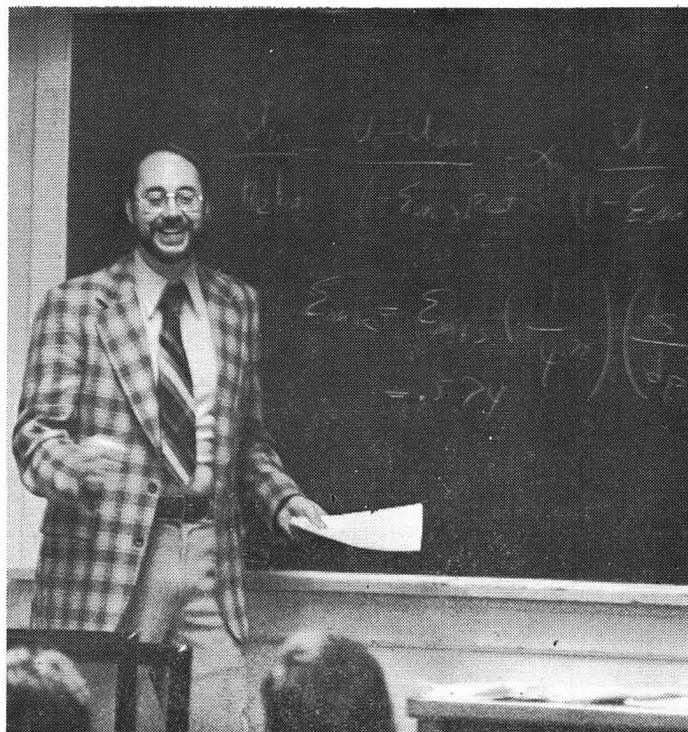
Union Carbide Corporation  
Dow Chemical U.S.A.  
E. I. duPont de Nemours & Co.  
Stauffer Chemical Company  
The Upjohn Company  
Diamond Shamrock Corporation  
Celanese Corporation  
The Procter & Gamble Co.  
Shell Development Company  
BASF Wyandotte Corp.  
Exxon Chemical/Research & Engineering  
Fluor Engineers & Constructors, Inc.  
General Electric Company  
PPG Industries  
Weyerhaeuser Company  
Standard Oil Company (Ohio)  
International Paper Company  
Standard Oil Company (California)  
Standard Oil Company (Indiana)  
Ethyl Corporation  
Phillips Petroleum Company  
Monsanto Corporation  
Texaco, Inc.  
Eastman Kodak Company  
Rohm & Haas Company  
Continental Oil Company  
NL Industries  
Occidental Research Corporation  
Envirotech Corporation  
Adolph Coors Company

**Foundations:**

National Science Foundation  
The Camille and Henry Dreyfus Foundation

## Scott Fogler

### A Teacher Of Learning



SUBMITTED BY J. S. SCHULTZ

*University of Michigan*

*Ann Arbor, Michigan 48109*

SCOTT FOGLER ENJOYS teaching, enjoys students, enjoys the challenge of arousing interest in his classes, enjoys the fulfillment of accomplishment in his students. In short, he comes as close to a Teacher of Learning as one is apt to find as this typical statement from one of his students shows: "I believe he really cares about each and everyone of his students; how they are doing in his courses, in other courses; and in particular the problems that students have in understanding course material. He is a top man. I would like to see more dedicated men in the teaching profession like him."

Scott remembers his first class as a teacher. It was during his first summer as a graduate student at Colorado, and he was asked to fill in

---

**Another important influence in Scott's teaching career was an ASEE workshop he attended in 1969. It was led by A. A. Root, and catalyzed his interest in finding new approaches to teaching**

---

for a month, teaching a rate operations course for juniors. Beginning teachers usually experience a combination of exhilaration and fear: Scott felt both. He loved the teaching, and the experience was a major reason why he decided to teach. But he also had fears.

"What if I teach all my life . . . and do it ineffectively?" Scott has paid attention to not doing it ineffectively. His sensitivity to students' interests, mastery of teaching techniques and communicable enthusiasm produce classes which challenge—and entertain—his students. He moves about the room, gesturing, poking at formulas on the board. He pauses for effect. He calls students by their first name, asking questions, and throwing in one-liners that keep the class alert and entertained. As one student says: "He's got to be good to keep a class this awake at 8:00 in the morning!"

An intensity and deep involvement pervades most of Scott's activities. He is always a man in motion striving for perfection—in class, in research conferences, in faculty meetings—his intense persistence on goals and achievements sometimes exhausts the efforts of others to keep up his pace.

## INFLUENCE OF TEACHERS

SCOTT'S ENTHUSIASM for teaching is explainable. His father was a professor of chemistry at Illinois State Normal University, in Bloomington, Illinois. His father's example and Scott's own intellectual curiosity proved a decisive combination: he gave up his interest in competitive swimming after graduating from Morgan Park High School in Chicago to devote more time to his studies. At the University of Illinois, where he received a BS (in 1962) he studied with Max Peters, one of the influential teachers in Scott's life. He was so impressed with Peters that he followed him to Colorado in 1962 when Peters accepted the Deanship there.

At Colorado, Scott had the fortune of working with Klaus Timmerhaus, another master teacher. From Timmerhaus, Scott learned the significance of maintaining an open, permissive atmosphere for students. He learned how to let students confront problems in their own way, and to learn from mistakes as well as successes. In this stimulating environment, Scott was encouraged to start his own seminar in interfacial phenomena as a graduate student.

After receiving his PhD in 1965, Scott joined the Faculty of The University of Michigan. Beginning the following year, he fulfilled his ROTC obligation, spending two years at the Jet



The Fogler Tribe.

Propulsion Laboratories. There, he also taught evening courses in mass transfer through UCLA's evening extension program.

Another important influence in Scott's teaching career was an ASEE workshop he attended in 1969. It was led by A. A. Root, and catalyzed his interest in finding new approaches to teach-

ing. Always a hard-driving perfectionist, Scott first dug into the literature of learning theory and developed a comfortable ease with the concepts and language for the analysis of educational approaches. "Open-ended, programmed learning, guided design, computer gaming, simulation, information dissemination, Keller plan, synthesis, motor skills," etc. were only some of the concepts that Scott brought to the Chemical Engineering Faculty over the next few years. At first, these were but abstractions to the rest of the faculty, but Scott made them real by applying them to his classroom activities. The results are remarkable, as students and colleagues attest. Scott has confronted the problem of individualized instruction in large classes with success. At least,

---

**Scott uses audio-visual materials in other ways such as in computer graphics. He currently has six interactive computer programs, two of which are played like games. One game is a murder mystery and uses knowledge of rate reactions to find the body and determine the murderer.**

---

the students think so: "I feel that I participate more actively in Professor Fogler's classes as one student in 80 than in some other classes where I am one out of ten."

Scott Fogler's teaching techniques are aimed at a double goal: to convey basic information, and also to teach the process of creative problem solving. His classroom approach reflects this philosophy. Scott spends class time telling his students about analysis and synthesis; how he thinks when he tries to solve a problem. He constantly asks himself "What intellectual ability am I teaching?" What he strives for is not just the factual basis for problem solving, but the creative ability to choose the best way of finding solutions. He feels that lab sessions are a time when the student should use his own intellectual arsenal for problem solving. Learning factual material, deriving equations and other "book work" is for the students' own time, out of class.

## CHALLENGING STUDENTS

SCOTT CALLS TEXTBOOK exercises "... convergent: if you work the formulas long

enough, you'll come up with the right answer. The world isn't like that. In industry, you may not know even if there is a problem. And if there is a problem, it may not have an answer or it may have many answers."

Scott reaches for "divergent" exercises, ones which challenge the student to use all his abilities for analysis and the synthesis of a solution. One of his favorite projects in an open-ended laboratory course he developed is a microplant. This is

---

**Scott has confronted the problem of individualized instruction in large classes with success. At least, the students think so: "I feel that I participate more actively in Professor Fogler's classes as one student in 80 than in some other classes where I am one out of ten."**

---

a continuing effort, begun several semesters ago, which is continued by succeeding classes. The project is a miniature plant for manufacturing polystyrene. It has progressed through the design to the hardware stage. Presently, after three years of student efforts, it produces small quantities of polystyrene. Continuing student efforts are directed to improving the product and increasing plant efficiency.

A student may be called on for abilities completely outside chemical engineering to solve problems in Scott's classes. Another project is to dramatize some classic material in ChE in a 10-minute videotape. The effort injects creative problem solving into the perfunctory experiments every chemical engineer has to know.

Scott uses audio-visual materials in other ways, such as in computer graphics. He currently has six interactive computer programs, two of which are played like games. One game is a murder mystery and uses a knowledge of rate reactions to find the body and determine the murderer. It must be in the processing vat because its conversion shifted dramatically at about the time of the murder. Each time the student signs on the computer, there will be a new randomly selected murderer and victim. The other computer game is more immediate: the student is told he has just been infected by a lethal bacteria. He has only a few minutes to perform a limited number of experiments. The first problem: which experiments

must he choose? The student who becomes too engrossed in experimentation will be told abruptly that he has taken too long, and has just died. As this game demonstrates, Scott feels that experimentation must be taught as a method of creative problem solving, and not as an end in itself. He cautions students to experiment economically, to try to reach the best solution with the fewest possible tests.

Another interactive computer graphics program simulates a microplant which has randomly-selected faults. With this program, each student is confronted with a unique diagnostic problem. For example, one of the components, such as a reactor, may be malfunctioning. Through a series of interactive diagnostics the student must find the faulty unit and suggest corrective measures. This sophisticated simulation took about three years to complete.

Scott is very concerned that the student be allowed to develop at his own speed whenever possible. He has tried the Keller plan of teaching, which allows individual rates of progress, but found that the need for proctors made the plan difficult.

One of Scott's techniques for large classes is straight out of Education School: the Buzz Group. Scott gives a brief lecture, and the students then break up into small groups to solve a class problem. As they work, Scott goes from group to group, encouraging, answering questions, probing. With this method, he can, in fact, provide a personal touch even in classes of 80 students.

Scott's greatest success to date with individualized learning is his *Programmed Text in Chemical Reaction Engineering (PTCRC)*. In this text, the student learns incrementally, frame by frame, pretty much at his own pace. One of the first texts of its kind in ChE, it is in its second printing in just three years.

## RESEARCH PROGRAM

**S** COTT REALIZES THAT masterful teaching techniques are not enough to keep a Professor

---

**Now, there are six PhD students doing research with Scott, and he has a bibliography of over 35 publications and over \$125,000 per year in research funding.**

---

going: "To have any impact on teaching, you need to have a sound research program before anyone will listen to you. I had some early ideas about guided design, but my research program really wasn't where it is now." Now, there are six PhD students doing research with Scott, and he has a bibliography of over 35 publications and over \$125,000 per year in research funding. In the beginning, Scott's own research interests came before his interest in teaching. He decided to pursue a PhD because he found he liked research after a summer project with John Quinn at the University of Illinois. It was that summer class in rate operations at Colorado that convinced him to teach. Scott started his research career with Klaus Timmerhaus in the area of ultrasonics. His interest in ultrasonics expanded at The University of Michigan to include some pioneering work on ultrasonic emulsification, and he recently achieved a breakthrough in predicting liquid-liquid droplet breakup dynamics in an ultrasonic field based on fluid mechanical and interfacial considerations.

Scott has become deeply involved in the kinetics and mechanism of heterogeneous interfacial dissolution of minerals, especially as applied



Scott's graduate research group holds a weekly seminar.

to improving oil and gas recovery (acidization) in porous rock formations. Scott is especially excited about his recent development of a mathematical model that predicts the movement of reaction and permeability fronts in porous media.

In related work, he has applied a fundamental kinetic approach to obtain some very strong leads on the interrelationship of acid attack on minerals, based on the crystal structure of the mineral and the behavior of interfacial reaction systems. One colleague commented that Scott was the first person to study the fundamental reaction of minerals in contact with acids, and his work will

---

**He is proud of the Dow Award he received in 1972, a recognition given to outstanding young faculty in the mid-west. Scott has been honored by the University of Michigan class of 138 E as an outstanding young faculty member, and has also received the U-M Junior Faculty Award.**

---

be of lasting importance to investigators in that field.

In addition to his research interests, Scott spends time consulting for Chevron Oil. He agrees that constant industrial contact is necessary for one who is training future chemical engineers. He brings as much non-proprietary data as he can to his classes.

Scott's enthusiasm for teaching—and doing it right—has won him recognition as an outstanding educator. He is perhaps most proud of being a Fulbright Scholar to Norway in 1974-75, at the Physical Chemical Institute of Bergen. While there, he studied flow and reaction in porous media, specifically the North Sea Oil wells. He is also proud of the Dow Award he received in 1972, a recognition given to outstanding young faculty in the mid-west. Scott has been honored by the University of Michigan Class of '38E as an outstanding young faculty member, and has also received the U-M Junior Faculty Award. Scott also remembers with pleasure the Annual Canoe Trip Seminar at the University of Pennsylvania: the invited guest gives an informal seminar after a scenic canoe trip.

#### OUTSIDE THE CLASSROOM

SCOTT'S ENTHUSIASM and intensity pervades most of his activities, both inside and outside the University. He is very much involved in the activities of his family, and through his children, has become very active in Little League and Indian Guides.

Indian Guides teaches the virtues of self-reliance, honesty, and concern for others through bi-weekly meetings, and other activities such as camping and canoeing. It emphasizes participation by the father-son team; in this case, Scott and his sons Pete, age 11 and Robby, age 9. Robby also shares his dad's affinity for scary movies, and periodically they share an evening of pleasurable fright.

Continued on page 36.



**ChE** department

## **PENN STATE**

JOHN M. TARBELL

*With Historical Notes by Floyd L. Carnahan  
University Park, Pennsylvania 16802*

**T**HE PENNSYLVANIA STATE University is one of the major academic institutions in the United States. With a total enrollment of about 67,000 in 1976, it ranked 11th nationwide. About 33,000 students are located at the main campus, University Park, with the remainder distributed among 20 branch campuses throughout Pennsylvania. Except for the University's College of Medicine at Hershey, the major graduate programs are located at the University Park Campus, as are the approximately 6,000 graduate students.

You may also have noted that Penn State has a football team.

The University Park Campus is on a 4,786-acre tract of land, of which 540 acres comprise the central campus. There are 272 major buildings at University Park but the many large shade trees and expanses of lawn give much of the campus a park-like appearance. The University is associated with the town of State College, a name dating back to a time when the University itself was a college. The permanent town population is somewhat smaller than the University's and no major industries are based in State College. As a consequence, most of the town's business activity is directed toward serving the University popula-

tion, offering shops, restaurants, entertainment and residences for many of the students.

The University, which was originally established as the Farmer's High School in 1855, is located in an almost completely rural section of the state, very close to its geographical center. The Appalachian Mountain range and nearby forested mountains and state parks offer a wide variety of outdoor activities throughout the year. These are balanced by the many cultural events and facilities found on campus. Penn State offers a quality education in a relaxed, coherent atmosphere without the distractions and disadvantages of the large city locale of many comparable institutions.

### DEPARTMENT ROOTS

Chemical Engineering at Penn State had its roots in Chemistry which separated from General Science in 1888. Dr. George Gilbert Pond was the first Professor of Chemistry. He and one instructor taught all the chemistry offered in 1888. The first chemistry graduate in 1890 was William H. Walker (now generally recognized as "the Father of Chemical Engineering"). Walker went on to Göttingen for M.A. and Ph.D. degrees and returned to Penn State as an Instructor in Chemistry (1892-1894). He moved to M.I.T. in 1894 where he established the School of Chemical Engineering Practice (1917) and collaborated with W. K. Lewis and W. H. McAdams in writing the first ChE textbook, the classic "Principles of Chemical Engineering" (1924).

A curriculum in Industrial Chemistry at Penn State was first offered in 1902 under Jesse B. Churchill. The distinctive element of this new curriculum was its emphasis on integrated chemical processes with stoichiometry and material balances serving as powerful practical tools of analysis. In 1924 with formation of the new School of Chemistry and Physics, the curriculum was renamed Chemical Engineering, and the then modern unit operations approach to chemical

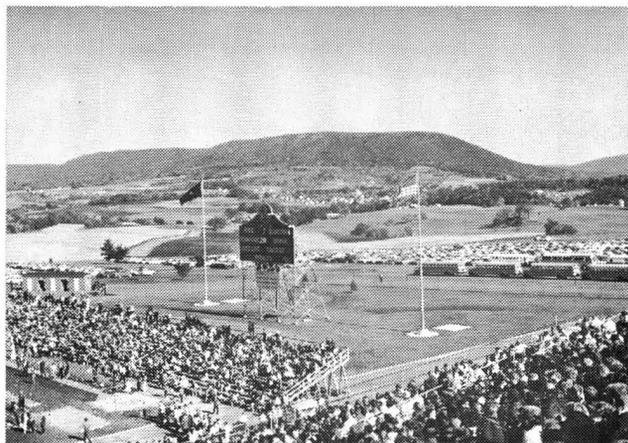
---

**The department established its early reputation through its pioneering research in petroleum processing and lubrication and these continue to be active research areas.**

---

process design and analysis was promoted with the aid of the new Walker, Lewis, and McAdams textbook.

Early in 1929 Merrell R. Fenske (Sc.D., MIT, 1928) became associated with the School of Chemistry and Physics in a research and instructional capacity. With distillation equipment of unique design installed in Pond Laboratory, he began studies on the composition of the lower boiling fractions of Pennsylvania crude oil. Exciting results came quickly; industrial and government support proliferated; and in 1931 additional laboratory space was obtained in the Old College Power Plant. These were the humble origins of the soon to become internationally recognized Petroleum Refining Laboratory. The laboratory was strictly a research organization staffed mainly with chemical engineers and chemists, as many as 70 during World War II. Techniques developed in the Petroleum Refining Laboratory helped insure an adequate supply of aviation gasoline, hydraulic fluids, and a variety of lubricants which



**A view of Mount Nittany from Beaver Stadium.**

were essential to the Allied War effort.

The Chemical Engineering and Chemistry Departments were separated in 1948 with Donald S. Cryder (Sc.D., MIT, 1930) as Head of the former. Vigorous interaction between the Petroleum Refining Laboratory and the Department of Chemical Engineering resulted in a merger in 1959 with Dr. Fenske as Head. Dr. Fenske reigned until his retirement as Department Head in 1969. The search for his successor consumed a year's effort, and in 1970 Lee C. Eagleton, formerly of the ChE Department at the University of Pennsylvania, became Head.

## THE FACULTY

**T**HE DEPARTMENT ESTABLISHED its early reputation through its pioneering research in petroleum processing and lubrication and these continue to be active research areas. Professors McCormick, Jones, Klaus, Tewksbury, Peiffer, and Barton grew up with the Petroleum Refining Laboratory and they carry on the fine traditions of that organization. In the late '50's and early '60's, ChE research and education experienced a fairly universal drift toward more fundamental ChE science. Penn State kept pace with this current by acquiring Professors Engel, Daubert, and Kabel whose fields of expertise (optimization, process dynamics, reaction kinetics, and complex phase equilibria) were expanding rapidly at that time. In the late '60's and early '70's, Professors Danner, Eagleton, Ultman, and Duda strengthened departmental efforts in phase equilibria and reaction kinetics while adding new expertise in interfacial and transport phenomena, polymer processing, and biomedical engineering. Most recently (1976), the addition of Professors Vannice and Tarbell (with their major interests in heterogeneous catalysis and applied mathematics) has rounded out the current faculty.

Although as a group we are most proud of our technical abilities and accomplishments, there are those who would argue that the true measure of a man's worth is the breadth of his interests. For example, when Dr. Eagleton first arrived on campus in 1970, he was shocked to find that no one on the faculty played tennis (Lee was seventh man on the tennis team at MIT one year, but never won a match). As a perceptive administrator, he quickly recognized this deficiency and soon convinced Dr. Danner (as Assistant Professor at the time) that tennis might be an important component of his professional development. Ron was obliging and served admirably as a partner until he received tenure, at which point his tennis enthusiasm suddenly waned. This situation was alarming and an exhaustive search for new talent was undertaken. Fortunately, Dr. Duda (whose background in polymer science was surpassed only by his twenty years of tennis experience) was looking for an academic position at that time. Larry and his wife were conveniently lured away from Dow Chemical Company to complete a formidable mixed doubles opponent for the Eagletons.

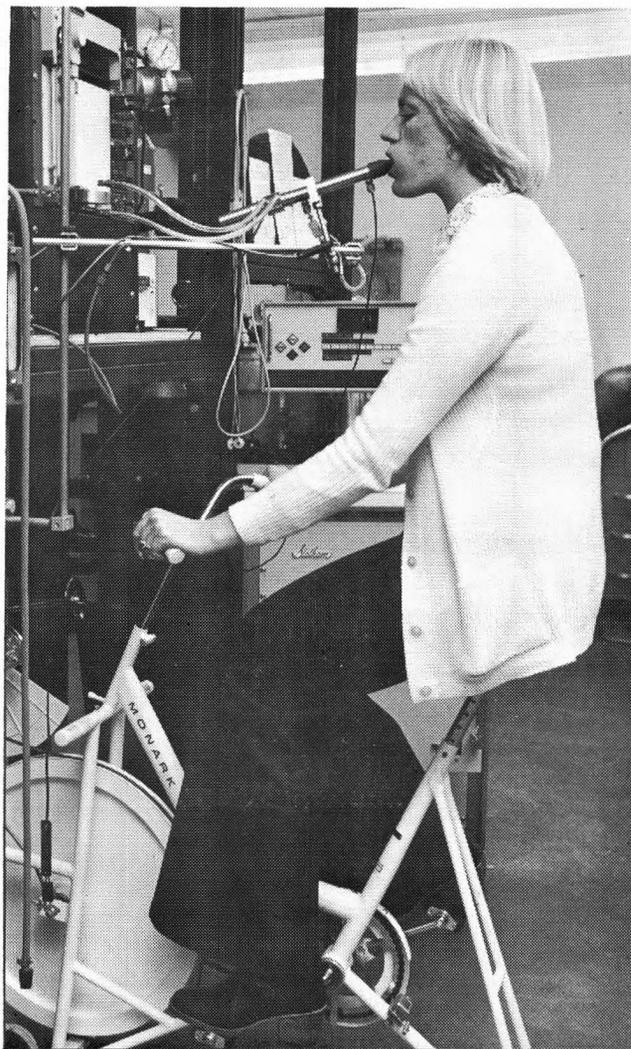
The competitive spirit in the department is perhaps best exemplified by the infamous Kabel-

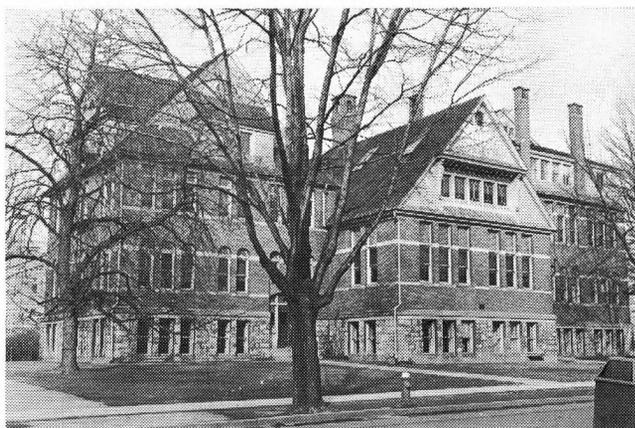
Danner squash rivalry. It is now widely accepted by members of the faculty that our weekly departmental meetings must not be scheduled on Monday, Wednesday, or Friday at 4:00 p.m. since these hours are forever reserved for the most pressing faculty activities. Beyond squash and tennis, these have often been known to include graduate student tutorials at the local pubs of State College.

In addition to his squash exploits, Dr. Kabel is also noted for his ability as an amateur aviator. A few years ago when Bob's research activity suddenly switched from reaction kinetics to air pollution meteorology, many on the faculty were baffled. In retrospect, this phenomenon is not difficult to explain. In what other field is it possible to include flying time in the budget of a research grant?

Community service is another area in which our faculty excel. Dr. Engel and Dr. Duda are active in the local Boy Scout troop. With their vast knowledge of outdoor life, they are uniquely qualified to lead twelve year old boys on expedi-

**Student performs in a pulmonary gas mixing experiment.**





**Walker Laboratory.**

tions through the fields and streams of Pennsylvania. Recently, Al and Larry were observed returning to State College late one Sunday evening with a mysterious L-shaped canoe on the roof of Larry's station wagon. Al was overheard saying, "Maybe next time we ought to try something a little less ambitious like a weenie roast in your back yard, Larry."

Actually, the departmental naturalist is Dr. Jones. On Mondays at lunch (while others are involved in lively discussions of the latest Penn State gridiron battle), Jennings sits alone in the corner offering a dissertation on his latest observations of the mating habits of the beardless fly catcher.

If modern music turns you on, then you will surely find the ChE trio (Danner—piano, Vannice—banjo, Ultman—vocals?) an inspiration. Their performances, usually reserved for intimate faculty dinner parties, are among the leading examples of dissonance available on major university campuses.

The list of faculty interests could go on, but surely at this point it is not difficult to conclude that ChE at Penn State is a truly catholic department.

### THE UNDERGRADUATE PROGRAM

**T**HE UNDERGRADUATE ChE curriculum at Penn State has experienced considerable evolution since the industrial chemistry era. The table below compares the curriculum as it appeared in the 1923-24 catalog with the current (1977-78) curriculum.

Although the total credits required for a degree has declined slightly, this has been mainly in non-technical areas. The major change has been the shift away from chemistry (55 credits then,

<u>1923-24</u>	<u>1977-78</u>
Industrial Chemistry (15 credits)	Chemistry (23 credits)
Chemistry (40 credits)	Engineering—required (35 credits)
Engineering (23 credits)	Engineering—elective (15 credits)
Mathematics (14 credits)	Mathematics (18 credits)
Physics (12 credits)	Physics (11 credits)
Other Courses (46 credits)	Other Courses (37 credits)
<u>Total—150 credits</u>	<u>Total—139 credits</u>

23 credits now) toward engineering (23 credits then, 50 credits now). The component of this change which pleases us most and which we feel best serves the interests of our students is the present 15 credits of engineering electives. This flexibility allows our seniors to pursue specialized

---

**Two students comprised the first Penn State graduating class in ChE Engineering (Industrial Chemistry 1906). This year we expect to graduate 105 students with B.S. degrees in ChE.**

---

courses of their choice in such areas as mathematical modeling, process dynamics, cryogenic engineering, nuclear chemical engineering, and polymer processing as well as in advanced offerings in process design, petroleum technology, industrial chemistry, transport phenomena, mass transfer operations, thermodynamics, chemical reactor design, and a host of courses in other engineering departments.

Also available is the senior research option which typically involves the student in an on-going departmental research project wherein he is exposed to research methodology and obtains "hands on" experience in a specialized field. During each of the past four summers, the department (with support from the National Science Foundation) has sponsored between 10 and 15 undergraduate students on departmental projects related to energy-environment problems such as tertiary oil recovery and catalysis for SO<sub>2</sub> oxidation. Not only Penn State students, but students from neighboring departments in the northeast have participated in this program.

Two students comprised the first Penn State graduating class in ChE Engineering (Industrial Chemistry—1906). This year we expect to graduate 105 students with B.S. degrees in ChE.

During the interim, 2,176 B.S. degrees were granted by the department.

### THE GRADUATE PROGRAM

**P**ENN STATE'S GRADUATE faculty in ChE offers programs leading to the M.S. and Ph.D. degrees. Over the years we have awarded 310 M.S. and 104 Ph.D. degrees. However, the number of graduate degrees awarded has accelerated in recent years with 20 M.S. and 4 Ph.D. degrees granted in 1976-77. For the last several years we have maintained a graduate population of 50 to 60 students and at the present time about 30% of our graduate students are working toward the Ph.D. degree. The department supports graduate students with fellowships, teaching assistantships and research assistantships. The primary vehicle for support is the half-time research assistantship which allows students to get deeply involved in their thesis projects early in their residence on campus.

The environment of our graduate program provides a unique opportunity for cultural exchange. We currently support students from the Far East, the Middle East, India, Africa, Western Europe, Latin America, and, of course, the United States. We have all been enriched by personal relationships developed with individuals of diverse backgrounds in both academic and social activities.

Our graduate students carry out most of their research work in the department's 35 individual laboratories and four story pilot plant. The ChE shop is well equipped and is staffed with two full time technicians who assist students in the design and construction of experimental apparatus. We are fortunate to be part of a large university for this allows us ready access to the facilities, programs, and expertise of its many fine departments. Interdisciplinary research projects with the University's Center for Air Environment Studies, Applied Research Laboratory, Milton S. Hershey Medical Center, Materials Science Department, Mineral Engineering Department, Meteorology Department, and Bioengineering Department have proliferated in recent years. This trend will surely continue as the technological problems facing society demand increasingly sophisticated solutions.

Beyond their usual interaction with the Penn State faculty, graduate students have the opportunity to listen to and indeed speak to many visiting academics and industrialists as a part of

the ChE seminar program. During the past year, 26 seminar speakers representing 10 universities, 10 industrial corporations, and several government agencies spent a day or more as guests of the department.

Of course, the faculty's research interests have the greatest influence on the character of the graduate program.

### VARIED RESEARCH

**R**ESearch AT PENN STATE covers a gamut from the applied to the fundamental in both classical and modern areas. Many projects embrace several disciplines, but in what follows current research is classified under broad and conventional labels.

#### • Energy and Environment

A major effort in tertiary oil recovery under the direction of Professors Klaus, Duda, Danner, and Jones is aimed at perfecting chemical flooding technology. This requires the development of surfactant synthesis strategies, and physico-chemical measurements of the phase equilibria, interfacial tension, and bulk viscosity of surfactant solutions. The surfactant solutions are non-Newtonian, viscoelastic fluids and their flow in porous media characteristics are being studied with a view toward designing an optimal solution based on a characterization of the porous media.

Greater understanding of the fundamentals of lubrication, friction, and wear (tribology) can

---

**Also available is the senior research option which typically involves the student in an ongoing departmental research project wherein he is exposed to research methodology and obtains "hands on" experience in a specialized field.**

---

result in improved lubricants which might save 5 to 15 percent of the gasoline consumed by the U.S. automotive fleet. Elmer Klaus and Elmer Tewksbury are studying the fundamental adsorption, chemical reaction, and film removal processes which underlie boundary lubrication with the goal of developing improved lubricants.

Al Engel is investigating the catalytic hydrogenation of algae to form an "oil" product which may serve as an energy source. An oil of acceptable quality has been produced and now

the reaction mechanism is being probed in order to develop a preliminary reactor design for economic evaluation.

Chuck Peiffer is looking at cocurrent contacting as a means of saving energy in separation processes by reducing the pressure drop required for a specified thru-put and separation.

The effect of combustion modifications for the control of nitric oxide emissions on the fuel economy of utility boiler systems is being evaluated by John Tarbell. Detailed mathematical models are used to simulate utility boiler operation with special emphasis on coal combustion and fuel nitrogen conversion. In related work, Al Engel is looking at catalytic processes for the oxidation of  $\text{SO}_2$  in stack gases.

Bob Kabel is involved in air pollution meteorology with emphasis on the natural removal of atmospheric pollutants at the earth's surface. Mechanisms of removal and the prediction of mass transfer coefficients for the atmosphere, large bodies of water, vegetation and soil are being investigated with the aid of an aircraft measurements program.

Paul Barton is currently performing a field evaluation of limestone treatment of industrial acid waste waters. His other projects include dewaxing of petroleum oils with crystallization by direct contact with liquid freons, molecular sieve separations with dense gas volatility amplification, and modeling of multi-stage Purex extractions of nuclear fuels in short residence time contactors.

#### • Kinetics and Catalysis

The vapor phase oxidation of organic compounds such as hydrocarbons, alcohols and aldehydes leads to a host of products depending on the reaction conditions. Jennings Jones has been studying the effect of temperature, pressure, and reactor surface conditions on the yield and selectivity of these complex reactions. In related work, Tom Daubert has been investigating surface effects in complex hydrocarbon oxidative dehydrogenation reactions.

Bob Kabel is attempting to elucidate the most important parameters in selection, preparation, and application of non-noble metal catalysts for the abatement of automotive exhaust pollution. Al Vannice is studying the effect of preparative variables such as solution pH, metal salt, and type of support, on metal dispersion in catalyst preparation. These projects aim to reduce catalyst preparation to a science rather than an art.

Al Vannice is also involved in a kinetic study of a new family of catalysts for  $\text{CO}/\text{H}_2$  reactions viz., metals supported on carbon molecular sieves. These sieves can be prepared with different pore size distributions to alter diffusivity which in turn affects product distribution. In addition, Al is using infrared spectroscopy to determine the effect of metal-support interactions and metal crystallite size on the adsorbed state of intermediates in methanation and Fischer-Tropsch reactions.

---

During the past year, 26 seminar speakers representing 10 universities, 10 industrial corporations, and several government agencies spent a day or more as guests of the department.

---

#### • Transport Phenomena and Thermodynamics

Larry Duda has been investigating diffusion in polymer solutions. Recent work has led to a new sorption technique for determining the concentration dependence of diffusion coefficients, and a new theory for the prediction of concentration, temperature, and molecular weight dependence of diffusion coefficients in concentrated polymer solutions. Related efforts are concerned with the thermodynamics and statistical mechanics of polymer solutions and the coupling of relaxation and diffusion in polymer systems.

Jim Ultman is studying the mechanism of gas mixing in lung airways and its role in pulmonary function testing. Tracer impulse-response techniques are used to measure the residence time distribution of the bronchial tree. Further work along these lines involves the development of a continuous monitor of lung compliance and blood oxygen concentration to aid the physician attending an infant suffering from hyaline membrane disease.

John Tarbell is determining the radial transport characteristics of periodic flows with secondary motion. These flows arise naturally in the human circulatory system when blood travels through curved arteries and branching vessels and may play an important role in the pathogenesis of arteriosclerosis.

The prediction and correlation of thermodynamic and transport properties for materials

Continued on page 47.

EDITOR'S NOTE: This paper continues a feature begun by CEE in the Summer 1976 issue. If you have a paper to submit, please send it to the editor.

## THE PROSPECTS OF POPULATION BALANCES

D. RAMKRISHNA

*Purdue University*

*West Lafayette, Indiana 47907*

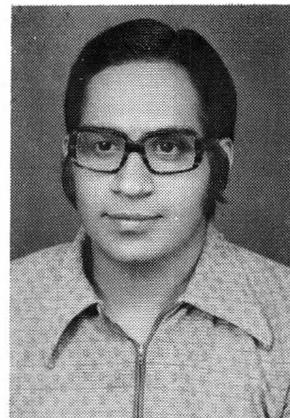
**T**HE DISPERSION OF one phase into another has been the crux of the chemical engineer's craft for carrying out a host of transfer operations. Thus, numerous separation processes based on direct phase-contacting such as liquid-liquid extraction, distillation, absorption etc. are conducted in dispersed phase systems. There are others that are essentially particulate in nature such as crystallization, fluidization, comminution, microbial growth, etc. The behavior of such systems is a complex combination of processes occurring at the single particle level. Thus, each individual particle may participate in rate processes (such as by its neighborhood in the continuous phase being under non-equilibrium conditions) and in processes such as *breakage* and *agglomeration* with other particles, that continually *destroy the identity* of existing particles.

The method of population balances falls somewhat naturally into the mathematical treatment of dispersed phase systems but for a variety of reasons, the methodology has not been adequately exploited. A notable exception is, perhaps the area of crystallization, mainly due to the efforts of Randolph and Larson [1]. Chiefly among the reasons for the unpopularity of population balances are (1) the complexity of the integro-differential equations, which result from them, and (2) the lack of suitable experimentation to evaluate the models. It is the objective of this communication to provide an overview of progress in the application of population balances and to point to their lucrative credentials for further work.

### WHAT ARE POPULATION BALANCES?

**T**HE CENTRAL IDEA of population balances is to formulate a *number balance* equation for particles of each "type". Particles are identified by "types" that are quantified as *discrete* variables or more discreetly, as *continuous* variables. Any given type may be destroyed into, or formed from, other types. In writing a number balance for each type one is concerned with the "source" and "sink" terms for that type.

Population balances are essential for the description of systems in which not only are particles present but where the *identity* of individual particles is modified or destroyed by processes



**Doraiswami Ramkrishna** received his B(Chem)Eng. degree (1960) from the Bombay University Department of Chemical Technology and his Ph.D. (1965) from the University of Minnesota. After teaching for two years at Minnesota, he returned to India in 1967 and taught at the Indian Institute of Technology, Kanpur until 1974. He was a Visiting Professor at Wisconsin (1974-75) and at Minnesota (1975-76) and is now Professor of Chemical Engineering at Purdue University. He is a consultant to General Mills, Inc., Minneapolis. His research includes dispersed phase systems, stochastic modeling and applications, bioengineering and problems of general applied math interests. Normally quite gentle, he reacts rather violently to criticism of **cricket**.

such as breakage or agglomeration. The framework becomes somewhat redundant in situations where the identity is preserved permanently for all particles.

The description of rate processes of course proceeds through the formulation of the equations of transport phenomena. Thus, for example, to describe mass transfer in a single drop in a liquid-liquid extraction process, the required apparatus is furnished by the methodology of transport phenomena. However, this is true only insofar as the *identity* of the drop is preserved without disappearing into another type. Clearly, therefore in dispersed phase systems the population balance framework is essential. More detailed considerations have been presented elsewhere [2, 3].

### MATHEMATICAL FRAMEWORK

**T**HE PARTICLE "TYPE" is described by one or more *state variables*\* generally regarded as continuous. If a single variable is used then we refer to it as a *scalar* state variable as against a vector state variable for types described by more than one variable. The number of particles in the system is assumed to be sufficiently large that a *continuous* variable may be used to denote the total number of particles in the system. The choice of the state variables depends much on the system of interest. Generally, one must select all particle properties which determine completely the behavior of single particles.

Let the particle state be denoted by a vector  $\mathbf{x} = (x_1, x_2, \dots, x_s)$ , which is a set of  $s$  physical quantities, whose numerical values will identify a given particle (Particles of identical states are assumed to be indistinguishable). The fundamental quantity describing the population is the *number density* function,  $n(\mathbf{x}, t)$ , which is regarded as a smooth function of  $\mathbf{x}$  and  $t$ . It is the number of particles per *unit volume* of the state space. The total number of particles,  $N(t)$  in the system is given by

$$N(t) = \int n(\mathbf{x}, t) dV$$

where  $dV$  is an infinitesimal volume in the state space of dimension,  $s$ . Limits on the volume integral have been excluded by design to indicate that the integration extends to the entire state space.

\*Examples of state variables are particle size, age, temperature, concentration of some dissolved solute etc.; physical space variables may also be included.

The state of any given particle may change due to one reason or another. We are here referring to *continuous* changes in particle state in which the identity of the particle is preserved. Thus a change in particle size by "growth" such as in a growing crystal or a microorganism comes under the present context, whereas a size change due to, say particle breakage does not. Such changes in state can be frequently modeled on a physical basis, e.g. conservation principles. We denote the rate of change of a particle of state  $\mathbf{x}$

---

**There are other processes that are essentially particulate in nature such as crystallization, fluidization, communication microbial growth, etc. The behavior of such systems is a complex combination of processes occurring at the single particle level.**

---

by a vector function  $\dot{\mathbf{X}}$ , which may depend on  $\mathbf{x}$  and variables associated with the continuous phase.

For the purpose of deriving the population balance equation in the number density function, it is useful to regard the particles as *embedded* in a continuum which deforms in accordance with the *kinematic field* represented by the vector  $\dot{\mathbf{X}}(\mathbf{x})$ . (For the present we exclude variables connected with the continuous phase). By embedding the particles on this deforming continuum we imply that a particle at a point  $\mathbf{x}$  moves with the local velocity  $\dot{\mathbf{X}}(\mathbf{x})$ . Alternatively, no relative velocity can exist between the continuum and the particle. This viewpoint makes the derivation of equations particularly convenient. Besides in dealing with situations where particle state changes *randomly* about a mean rate, we may look upon the particles as *diffusing* in the continuum deforming with the *mean* velocity field.

Let  $h^+(\mathbf{x}, t)dV$  be the *rate* of increase in the number of particles in a volume  $dV$  about  $\mathbf{x}$  in the state space. Similarly we may define a *sink* function  $h^-(\mathbf{x}, t)$  so that the *net generation rate*  $h(\mathbf{x}, t)$  is given by

$$h(\mathbf{x}, t) = h^+(\mathbf{x}, t) - h^-(\mathbf{x}, t) \quad (1)$$

The population balance equation can now be readily written by invoking the continuity operator in the particle state space.

$$\frac{\partial}{\partial t} n(\mathbf{x},t) + \nabla \cdot \dot{\mathbf{X}} n(\mathbf{x},t) = h(\mathbf{x},t) \quad (2)$$

Equation (2) has been derived by Hulburt and Katz [4]. It must be coupled with mass balance equations for continuous phase variables (see for example [5]).

At this point, it must be pointed out that what we have accomplished is only the mathematical formulation of a rather obvious accounting principle for particle numbers. Equation (2) by itself is therefore not to be construed as a population balance *model*. The modeling lies in identifying the *nature* of the functions  $\dot{\mathbf{X}}$  and  $h(\mathbf{x},t)$  for a given situation.

As observed earlier,  $\dot{\mathbf{X}}$  may often be modeled by physical conservation principles and transfer coefficients. The function  $h(\mathbf{x},t)$  depends on the process by which particle-types appear and disappear. For example, communitation operations involve particle splitting. For such processes, one identifies a *specific rate* of splitting of particles of state  $\mathbf{x}'$  ( a transition probability function), say  $\Gamma(\mathbf{x}')$ , a function  $\nu(\mathbf{x}')$  representing the mean number of particles formed by splitting of a parent particle of size  $\mathbf{x}'$ , and a conditional probability distribution  $p(\mathbf{x},\mathbf{x}')$  for the sizes of particles formed from breakage. Thus for the present case we have

$$h^+(\mathbf{x},t) = \int \nu(\mathbf{x}') \Gamma(\mathbf{x}') p(\mathbf{x},\mathbf{x}') n(\mathbf{x}',t) d\mathbf{x}' \quad (3)$$

and

$$h^-(\mathbf{x},t) = \Gamma(\mathbf{x}) n(\mathbf{x},t) \quad (4)$$

When Equations (1), (3) and (4) are substituted into (2), the population balance model is completely identified. Of course boundary and initial conditions must also be appended. The important point to note is that the functions,  $\Gamma(\mathbf{x}')$ ,  $\nu(\mathbf{x})$ ,  $p(\mathbf{x},\mathbf{x}')$  are actually unknown and must be obtained by more detailed modelling of the splitting process, or must be inferred from suitable experiments.

Similar problems arise also in the modelling of agglomerating populations. Thus, consider a population of particles distributed according to their volumes, in which any two particles of volumes  $v$  and  $v'$  agglomerate in the time interval  $t$  to  $t+dt$  with probability  $q(v,v')dt$ . Then it is readily shown that

$$h(v,t) = \frac{1}{2} \int_0^v q(v-v',v') n(v',t) n(v-v',t) dv' - n(v,t) \int_0^\infty q(v,v') n(v',t) dv' \quad (5)$$

Again, the transition probability of agglomeration,  $q(v,v')$  requires identification by more detailed modelling and experimentation.

As pointed out earlier, the significant difficulties in the application of population balances are in the solution of the integro-differential equations, and in the identification of the probability functions which describe particle behavior. Some past work is reviewed here in regard to either of these aspects.

## SOLUTION OF EQUATIONS

SINCE, FREQUENTLY the leading moments of the number density function is a satisfactory description of the population, it has been suggested [4, 6, 7] that moment equations be directly obtained from the balance equation. Frequently, this leads to trouble either in the form of unclosed moment equations, equations with fractional moments, or those that simply do not directly yield moments. To overcome these difficulties, a Laguerre function expansion of the number density function, has been suggested [4]. These methods can be readily shown [8] to be a special (and therefore restricted) application of the method of weighted residuals. Thus, Subramanian and Ramkrishna [9] have solved population balance equations for a microbial population distributed according to their mass, in which individual cells grew by assimilating nutrient material from the environment and reproduced by binary division. Solutions for the population balance equation, which was coupled to the mass balance equation for the substrate concentration, were obtained using Laguerre functions as trial functions and orthogonalizing the residual with various choices of weighting functions.

The choice of the trial function is a vital aspect of success with weighted residual techniques. Thus, "standard" choices such as Laguerre polynomials can often be significantly improved upon. For example, one may generate "problem-specific polynomials" [10] from the set  $\langle x^n \rangle$  by Gram-Schmidt orthogonalization using suitably weighted inner products. A desirable weight function for the inner product should essentially have a shape and trend similar to that of the solution. The advantage of generating such polynomials as trial functions for solving population balance equations

by the method of weighted residuals has been demonstrated by Singh and Ramkrishna [11, 12]. Thus transient solutions have been obtained in which specifically generated time-dependent trial functions assure rapid convergence of the solution at all times[12].

When the particle state variable is a vector, the resulting multivariate number density functions are likely to be much harder to solve for. This problem requires further investigation. An alternative route to obtaining solutions, however lies in simulation techniques [13-17]. Although simulation techniques often involve arbitrarily discretizing the time interval, a recent method due to Shah et al [17], handles the artificial evolution of the system in an elegant manner by generating random numbers representing "intervals of quiescence". Each interval of quiescence is a period, in which every member of population retains its identity, and has an exactly calculable probability distribution. Thus no tests for the adequacy of the fineness of discretization would be necessary in such a simulation procedure.

#### MODEL IDENTIFICATION

**T**HE PROBABILITY FUNCTIONS characterizing random particle behavior must be identified before population balance equations can be quantitatively applied to real systems. As an example, consider the particle-splitting process re-

---

**The central idea of population balances is to formulate a number balance for particles of each "type." Particles are identified by "types" that are discrete variables or more discretely, as continuous variables. Any given type may be destroyed into, or formed from, other types.**

---

ferred to earlier, for which the model was defined by the functions,  $\Gamma(\mathbf{x}')$ ,  $\nu(\mathbf{x}')$ ,  $p(\mathbf{x}, \mathbf{x}')$ . A direct experimental determination of such probability functions is a very difficult task. With suitable additional modelling, however the problem may at times be tractable. In a liquid-liquid dispersion, with a low dispersed phase fraction coalescence between droplets is likely to be negligible during the temporal evolution of the dropsize distribution which primarily occurs by drop breakage. By proposing that the breakage probability function for

a drop of volume  $v$  is given by  $\Gamma(v) = kv^n$ , it can be shown [18] that the cumulative-volume distribution of drop-volume denoted  $F(v,t)$  has an explicit similarity solution in the variable  $v^nt$ , i.e.,  $F(v,t) = g(\xi)$ , where  $\xi = v^nt$ . In order to test this hypothesis, if experimental data on dropsize distributions are available at various times in a batch vessel, then a plot of  $\ln v$  versus  $\ln t$  for any fixed value of  $F$  should produce a straight of slope  $-n$ . Besides, parallel straightlines should be obtained if the plots are made for different fixed values of  $F$ . From the experimental data of Madden and McCoy [19], such tests have in fact shown [18] that a power law breakage model may be a good representation of  $\Gamma(v)$ . The similarity plot using the calculated value of  $n$ , can then be used to determine the size distribution of the droplets formed from the broken drop [18]. The data of Madden and McCoy yield approximately a value of 2 for the power  $n$ . Based on modelling drop breakage as a result of relative velocity fluctuations across the droplet surface, arising from the continuous phase turbulence, the application of Kolmogorov's theory of local isotropy appears to vindicate the power law expression with  $n$  having a value of about 2.67 [20].

As another example, one may consider denser liquid-liquid dispersions with high dispersed phase fraction. Since breakage and coalescence are both important in this situation the breakage and coalescence probabilities must be known. Following an earlier visualization by Curl [21] of the coalescence-redispersion process as a *single-step* process, Bajpai *et al* [22] proposed that droplets in a dispersion coalesce and immediately redisperse into two new droplets in a perfectly random manner. They solved the population balance analytically to obtain an *exponential drop-volume distribution* at equilibrium, which showed good agreement with experimental data from diverse sources.

The implication of the two preceding paragraphs is that there seems to be sufficient evidence pointing to the tractability of population balance models from an experimental viewpoint.

#### SMALL POPULATIONS

**P**OPULATION balance equations are essentially for describing the behavior of large particle populations in which random behavior of individual particles is averaged out. The number density function  $n(\mathbf{x},t)$  is the *expected* population density. Although most systems of interest in

Continued on page 43.

# TEACHING THE BASIC ELEMENTS OF PROCESS DESIGN WITH A BUSINESS GAME

T. W. F. RUSSELL AND D. S. FRANKEL  
*University of Delaware*  
*Newark, Delaware 19711*

In this paper we describe an educational tool which effectively illustrates how basic chemical engineering skills in reactor design and process analysis are combined with economic consideration to design a processing plant whose performance is tested by its ability to compete profitably in the market place.

Since it is not possible to actually build and test proposed designs, we have developed a business game to provide evaluation of the process designs in a more realistic fashion than by the usual procedure of grading a design report. The game also deals with the important aspects of competition and uncertainty in projected market, factors which are almost impossible to incorporate into most design teaching.

The game described in this paper requires the very simplest reactor, process and economic analysis. It was deliberately designed this way after some early experimentation so that the student would clearly see the interaction between the basic engineering skills, economic considerations and the need to have a profitable operation.

Class and student time required to complete the game varies with the sophistication of the students from 15 to 25 hours. More complicated forms of the game are under development which will take longer and require much more analysis.

## GAME FORMAT

ALL PARTICIPANTS are given a copy of Figure 1 which shows expected sales of product "D" and expected selling price at various sales levels. In addition the following information is given in memo form.

- (i) Chemical Equation  $A \rightarrow D$   
 (ii) Constitutive Relation for Reaction Rate

$$r_A = kC_A$$

$$k = 0.005 \text{ min}^{-1}$$

The simplest possible chemistry is chosen so that process design can be developed with a minimum of mathematical manipulation.

- (iii) The design equations for a continuous flow stirred-tank reactor

a) Component mass balance for A (1)

$$0 = q[C_{AF} - C_A] - kC_A V$$

b) Component mass balance for D (2)

$$0 = -qC_D - kC_A V$$

where

- $V$   $\equiv$  volume of fluid in the CFSTR, liters  
 $q$   $\equiv$  volumetric flow rate of fluid, into and from the CFSTR, liters/min  
 $k$   $\equiv$  specific reaction rate constant =  $0.005 \text{ min}^{-1}$   
 $C_{AF}$   $\equiv$  concentration of reactant A in the inlet stream, gm-mole/liter  
 $C_A$   $\equiv$  concentration of reactant A in the CFSTR and in the exit stream from the CFSTR, gm-mole/liter  
 $C_D$   $\equiv$  concentration of product D in the CFSTR and in the exit stream from the CFSTR, gm-mole/liter

The simple reactor is chosen so that those new to process design thinking are not over-

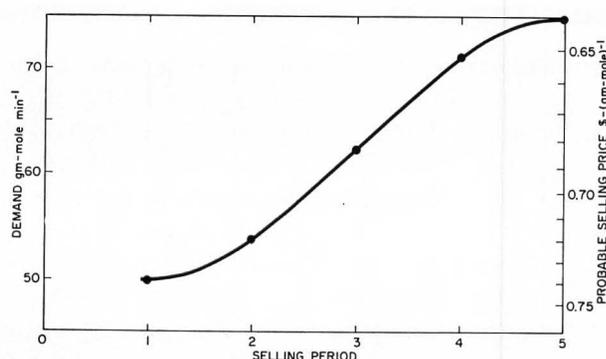


FIGURE 1. Sales Demand and Selling Price.

**T. W. F. Russell** is a Professor of ChE and Associate Dean of the College of Engineering at the University of Delaware. He obtained his bachelors and masters degree from the University of Alberta and after working as a design engineer with Union Carbide, Canada for three years, he obtained his Ph.D. from the University of Delaware. Professor Russell is a coauthor of "Introduction to Chemical Engineering Analysis" (J. Wiley 1972) and "Structure of the Chemical Process Industries—Function and Economics" (McGraw Hill, in press).

**Dave Frankel** will receive his Ph.D. from the University of Delaware in May 1978. He will be working for Exxon Production in Houston, Texas.

whelmed by mathematical computation. It is a simple matter to modify the memo to let more experienced students develop their own design equations.

(iv) The concentration of raw materials A,

$$C_{AF} = 0.2 \frac{\text{g-moles}}{\text{liter}}$$

(v) A simplified process flow diagram as shown in Figure 2

(vi) Cost of reactant A, \$0.20/g-mole

(vii) Depreciated capital cost, maintenance costs and operating costs of the process unit are assumed proportional to the reactor volume V, and approximated as  $S_V = \$45/\text{liter-year}$

This is another simplification introduced to keep the algebra simple. The economics can be made more realistic by basing the separation column capital cost on unit throughput, q, and relating all operating costs to the unit throughput, q. This complicates the algebra but, because of the nature of the process, makes very little numerical difference from the simple expression given above.

(viii) Inventory charges will be \$ .10 per gm mole per year.

(ix) Operations which develop a debt of \$2,000,000 will be assumed bankrupt and not permitted to continue.

With the above information a process unit can be designed and then operated to produce product D for a simulated market with four companies. Each of the four companies must decide upon the reactor size that they will have in their process unit and how to operate it each year to produce a maximum profit. The game begins when each company has made its decisions and submitted to control the reactor size and the process unit output for year one. A typical set of such inputs is shown in Table I.

Once the size of the reactor has been specified the company cannot change it by adding addi-

tional capacity during the simulated five year operation of the game. Each company is of course free to manipulate feed rate, and hence conversion, to the reactor for each of the five periods.

Input data from each group is processed by control using the program shown on the Logic Flow charts presented in Appendix A. The program operates in the following manner.

- Input is checked for accuracy and internal consistency; i.e., a company could not call for a rate of production which would necessitate a larger volume of CFSTR than they had designed and built.
- The true total market demand is generated randomly within limits about the projection supplied to the players in Figure 1. Selling prices are computed concurrently.
- Sales are allocated to the companies by a simple algorithm based on previous market share and the projected sales which the company specifies on its input sheet.
- Profits, cumulative profits and inventories are computed.

The output is presented to each company in the following format:

- (i) Total Market
- (ii) Selling Price
- (iii) Company Sales
- (iv) Market Share
- (v) Profit for the Period
- (vi) Cumulative Profit.

The companies make their decisions for the next period based on these results. The game is

**TABLE I**  
A Typical Set of Input Data to Process Design Game.

Company	Reactor Size (liters)	Process Unit Output (gm-moles/year)
A	50,000	$9.25 \times 10^6$
B	42,700	$6.30 \times 10^6$
C	70,000	$6.20 \times 10^6$
D	77,300	$6.05 \times 10^6$

run for five periods and performance is evaluated by comparing cumulative profits.

#### CLASS EXPERIENCE

**T**O PROPERLY DEVELOP a game it must be played a number of times and modified as a result of the experience gained. To date this game has been played about ten times with most of the modifications carried out in the first three to five sessions. A listing of the course using the game is given in Appendix B.

In the first two games the companies were allowed to set the selling price as if the product were new on the market. Market share was partially based on this selling price in the control program and this gave the participants an extra degree of freedom to manipulate for market share. The scheme worked reasonably well for upper level students (seniors and first year graduate students in a technical management course) but turned out to be too complicated for the freshman-sophomore level student for which we were designing the game. We modified our procedure to the more realistic situation where price is determined by total market demand. The functionality is shown in Figure 1.

We next modified the game to add an inventory charge. This also is a more realistic simulation of what actually occurs in the real world. It is a

necessary element of the game which helps to prevent companies from "flooding" the market to gain a large market share.

A bankruptcy limit also was imposed after our initial experiences to make the game more true to life and to prevent companies from unrealistic operation in the initial periods to build up market share. We have found that a bankruptcy occurs about every second or third game. Sometimes this is because of deliberately aggressive action and sometimes because of error. When a bankruptcy occurs, the structure of the game changes markedly since the total demand must be met by three instead of four companies and companies who have designed a small reactor may find themselves at a considerable disadvantage.

A typical set of results is shown in Table II for the companies whose input data for period 1 are shown in Table I. In this particular game, Company D went bankrupt and Company C almost went bankrupt. The large reactors were unprofitable with four companies competing for the market and only became profitable when one company was forced out.

Some basic process analysis can be easily performed for this game since the simplest possible chemistry, and reactor type have been specified. It is also quite easy for students familiar with basic calculus to compute an optimum value for the conversion,  $C_A/C_{AF}$ . One can then compute the optimal volume for a given production rate as follows:

$$\begin{aligned} \text{Yearly Profit} &= \text{Income from Sales} - \text{Cost of A} - \text{Capital-Operating costs} \\ &= S_D q C_D Y - 0.20 q C_{AF} Y - 45V \quad (3) \end{aligned}$$

This yearly profit can be expressed in terms of the variable  $C_A$

$$= S_D q C_D Y - \frac{0.20 q C_D C_{AF} Y}{C_{AF} - C_A} - \frac{45 q C_D}{0.005 C_A} \quad (4)$$

where

$$\begin{aligned} S_D &= \text{selling price of D, \$/g-mole} \\ Y &= 504,000 \text{ min/year} \end{aligned}$$

This yearly profit can be differentiated with respect to  $C_A$  to yield a quadratic equation in the variable,  $C_A/C_{AF}$ , which can be solved to yield

$$\left. \frac{C_A}{C_{AF}} \right)_{\text{optimal}} = 0.4015 \quad (5)$$

The relationship between reactor volume and the throughput  $q$  is

TABLE II

Typical Set of Results for Process Design Game.

PERIOD 1

Projected Market	(Figure 1)	25.2 x 10 <sup>6</sup>	g-moles/
Actual Market	(Program)	26.2 x 10 <sup>6</sup>	year
Selling Price		\$0.73/	
		g-mole	

Company	Market Share	Conversion $C_A/C_{AF}$	Inventory 10 <sup>6</sup> g-moles	Cumulative Profit Thousands of \$
A	31.6%	0.40	0.97	590
B	23.1%	0.407	0.24	335
C	22.8%	0.191	0.22	-355
D	22.4%	0.23%	0.18	-811

PERIOD 2

Projected Market	(Figure 1)	27.2 x 10 <sup>6</sup>	g-moles/
Actual Market	(Program)	26.8 x 10 <sup>6</sup>	year
Selling Price		\$0.73/	
		g-mole	

Company	Market Share	Conversion $C_A/C_{AF}$	Inventory 10 <sup>6</sup> g-moles	Cumulative Profit Thousands of \$
A	35.6%	0.439	1.59	1,450
B	22.7%	0.407	0.41	473
C	23.7%	0.19	0.69	-1,010
D	20.4%	0.238	0.62	-2,430*

\*Bankruptcy!

PERIOD 5

Projected Market	(Figure 1)	37.8 x 10 <sup>6</sup>	g-moles/
Actual Market	(Program)	37.5 x 10 <sup>6</sup>	year
Selling Price		\$0.64/	
		g-mole	

Company	Market Share	Conversion $C_A/C_{AF}$	Inventory 10 <sup>6</sup> g-moles	Cumulative Profit Thousands of \$
A	28.5%	0.439	0.82	4,988
B	27.3%	0.511	0.95	2,089
C	44.2%	0.518	1.86	596
D	Bankrupt			

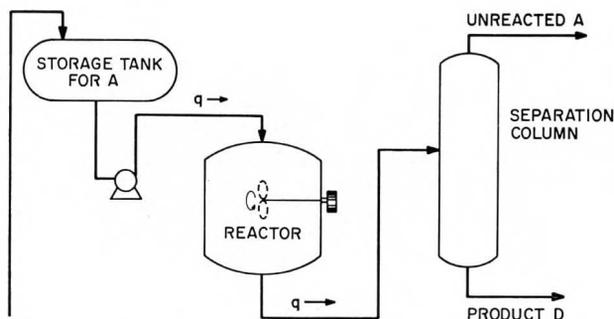


FIGURE 2. Process Flow Diagram.

$$V = 2490 qC_D \quad (6)$$

The simple analysis is a necessary step in the problem solution but it is far from sufficient to assure that one will have a good profit or in fact even a profitable operation. Two factors, competition and a growing market need to be considered. There is no theoretical analysis, sophisticated or simple, which can be carried out to deal with these two factors.

Most groups design their reactor to supply some share of the market (usually 30-40%) in years three or four. In the game shown in Tables I and II, Companies C and D felt they could capture a large share of the market so they constructed larger reactors than Companies A and B. Unfortunately, they did not operate them close enough to the optimal in the early years; they did not achieve large shares of the market and Company D went bankrupt. Had Companies C and D been more aggressive and operated with a higher throughput in years 1 and 2, they might well have forced Company B with the small reactor into bankruptcy. In this particular game, Company C had the best position with only three companies supplying the market. Unfortunately, they did not do the simple optimal analysis and as a result, operated with values of  $C_A/C_{AF}$  which were too low.

It is necessary for the students to draw upon learning experiences from several disciplines in order to make design decisions. We feel that the engineering game exercise was much more rewarding for introductory students than a dry optimization problem using only principles of the calculus. The game impressed upon the players that engineering is more than finding equations and plugging in numbers: it is more of an art in which the engineer, and not a textbook, must make decisions. Hopefully, this experience will enable the students to keep their coursework in its proper perspective, and discourage the point

of view that macroscopic balances and differential equations are all that is necessary to pinpoint an answer to any engineering problem.

The game captivated student interest in engineering, since the groups were always eager to receive and evaluate their output, and make decisions for the next selling period. The added feature of near instantaneous feedback makes the game approach valuable from an educational psychology standpoint.

The game also has worked surprisingly well with engineers and chemists with some considerable industrial experience. Some of our most enthusiastic players have come from this group of mature persons. We feel that this is partly attributable to the insights that are obtained with regard to the process analysis and partly attributable to the simple insights that are obtained into the economics of the chemical process industries.

---

**Since it is not possible to actually build and test proposed designs, we have developed a business game to provide evaluation of the process designs in a more realistic fashion than by the usual procedure of grading a design report.**

---

#### ACKNOWLEDGMENTS

We would like to thank all those who have helped us develop this educational tool by playing the game in its initial stages and providing us with feedback. Dr. R. L. McCullough of the Chemical Engineering Department of the University of Delaware and Mr. P. H. Bailey of the Engineering Department of the E. I. du Pont Company were kind enough to spend time on discussion and comment. We appreciate their efforts very much. The Dean's Office in the College of Engineering provided both funds and encouragement and we are grateful for this support. Mr. R. Pratt, Engineering Computation Specialist in the College of Engineering has been most helpful in setting up the necessary computer programs. One of us (TWFR) developed the initial idea while on sabbatical leave at the Swiss Federal Institute of Technology (ETH) in Zurich and I am appreciative of discussions with colleagues at that institution.

APPENDICES A&B FOLLOW.



**APPENDIX B.  
COURSES USING THE PROCESS DESIGN GAME**

- |  |   |
|--|---|
| 1) ChE 690<br>Technical Project<br>Management        | Fall 1973; Fall 1974<br>Seniors and graduate<br>students in chemical<br>engineering   |
| 2) EG 125<br>Introduction to<br>Engineering          | Fall 1973<br>Freshmen students in<br>chemical engineering   |
| 3) ChE 530<br>Engineering Analysis<br>for Non-Majors | Spring 1974<br>Junior and senior<br>students in chemistry<br>life science, mathematics<br>and electrical engineering                  |
| 4) ChE 667<br>Special Topics<br>Course               | Winter 1974 Session<br>A group of senior students<br>in chemical engineering  |
| 5) Engineering Analysis<br>for Chemists              | Summer 1974<br>A course for industrial<br>chemists—a group from<br>the Swiss chemical and<br>pharmaceutical industry                  |
| 6) Introduction to<br>Engineering                    | Spring 1975<br>A course to introduce<br>high school juniors to<br>engineering   |
| 7) Engineering Analysis<br>for Chemists              | Spring 1975<br>A course for industrial<br>chemists—a group from<br>the Organic Chemicals<br>Department of the E. I.<br>DuPont Company |

**ChE book reviews**

**CELLULOSE AS A CHEMICAL AND  
ENERGY RESOURCE**

*5th Symposium of Biotechnology and  
Bioengineering  
Plenum, New York. (\$25.00)*

Reviewed by Charles Walter, University of  
Houston

The 5th Symposium of Biotechnology and Bioengineering was about "Cellulose as a Chemical and Energy Resource." The organization of the topics includes contributions about "The Substrate," "The Enzyme System," "The Process," and "The Product."

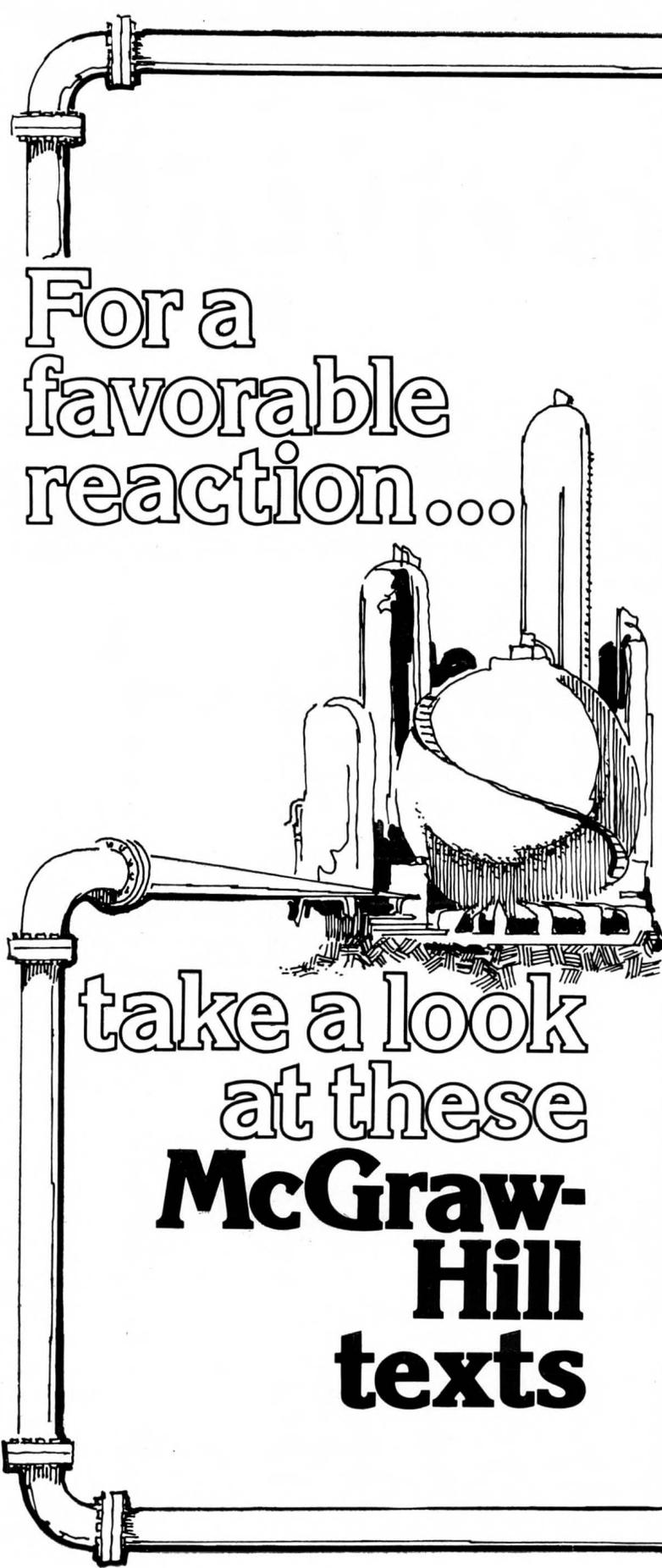
"The Substrate" is cellulose. In this section there is a weak chapter about cellulose economics which reflects confusion about scientific matters and relies heavily on meaningless figures (for example, the figures about cellulose conversion

into protein or ethanol, or alcohol conversion into adenesine triphosphate).

The remainder of the section about "The Substrate" is highly recommended. An excellent introductory statement establishes that the greatest portion of what we call waste cellulose is not really "waste" at all, and that processes utilizing the substrate must be economically viable. This theme is continued in a later chapter dealing principally with agricultural "wastes." Other chapters in this section contain excellent discussions of the relationship between energy input and energy yield for cropping systems and a specific cost analysis for producing plant biomass on a hypothetical plantation. This analysis leads to an optimistic estimate of about \$10/ton of dry biomass, or \$.65/10<sup>6</sup> Btu. The important chapter by Diaz puts into perspective however, that even if cellulose were obtained from "waste" sources that were "free," the substrates used as chemical or energy resources would be considerably more expensive due to the high processing costs involved. Bassham's chapter provides an excellent sketch of the overall energetics of cellulose production in green plants, including a discussion of the merits of C-4 plants versus plants without this extra CO<sub>2</sub> - fixing pathway, and an estimate of the photosynthetic efficiency expected for this process. The number Bassham arrives at is 5% which is about half the often-quoted maximum theoretical efficiency for photosynthetic processes.

"The Enzyme System" is cellulase but the worthwhile contribution to this section of the volume is about the action of H<sub>2</sub>O<sub>2</sub>/Fe(II) on cellulose—a process which obviously could lead to significantly lower costs for commercial cellulose digestion. This, together with the fact that many cellulolytic organisms apparently secrete little or no cellulase, is a compelling argument for more research on the H<sub>2</sub>O<sub>2</sub>/Fe(II) system and brown-rot fungi and less emphasis on isolated and reconstituted enzyme systems. The deep-seated prejudice that compels many biochemists to isolate biomolecules from their three-dimensional, functional environment and study their properties in an irrelevant setting dominates most of the other papers in this section. Judging from comments made in other sections of the volume (for example, "Too much of our existing knowledge about cellulose hydrolysis has been derived from studies with purified raw materials" by E. L. Gaden on page 161) many of the sym-

Continued on page 47.



For a  
favorable  
reaction...

take a look  
at these  
**McGraw-  
Hill**  
texts

### **Chemistry of Catalytic Processes**

Bruce C. Gates, G.C.A. Schvit, both of the University of Delaware, and James R. Katzer, Stanford University

The interrelationship of catalytic chemistry and engineering requirements is fully illustrated in this applications-oriented guide. The authors provide a much-needed overview of real world practices while covering the complexity of industrial catalysts. Each of the five chapters deals with an industrial process or class of processes. Quantitative examples are featured to illustrate design methods, and problems are included with each chapter, making the book an excellent graduate level text for courses in catalytic kinetics and reaction engineering.

1978, 512 pages (tent.), \$28.50 (tent.)

### **The Structure of the Chemical Processing Industries: Function and Economics**

J. Wei, Massachusetts Institute of Technology, T.W.F. Russel, University of Delaware, and M.W. Swartzlander, Union Carbide Corporation

This vital new text broadens the scope of chemical engineering students and practitioners by examining the organization and use of resources in chemical manufacturing; the economic and socio-political forces that affect the chemical process industry (CPI), and the need of the industry to adapt to these influences in order to survive. In exploring the complex role of the CPI in society, the book uses a variety of analytical tools, including microeconomics, production functions, game theory, financial analysis, basic accounting practice, theory of the firm, and input and output analysis.

1978, 640 pages (tent.), \$21.50 (tent.)

Solutions Manual and Instructor's Manual available

### **Biochemistry Engineering Fundamentals**

James E. Bailey, University of Houston, and David F. Ollis, Princeton University

This volume deals broadly with engineering fundamentals and applications of biochemical processes. In addition, the necessary biochemistry and microbiological principles are included, with special attention devoted to such topics as enzyme kinetics, bioenergetics, metabolic pathways, and molecular genetics. The volume stresses special engineering considerations, the mathematics needed by the biochemical engineer, environmental engineering, and the involvement of biochemical engineering practices in modern industry.

1977, 576 pages, \$25.50

## **Chemistry For Environmental Engineering, Third Edition**

Clair N. Sawyer, formerly of the Massachusetts Institute of Technology, and Perry L. McCarty, Stanford University

Here is a text that focuses on those aspects of chemistry particularly valuable to the practice of environmental engineering. It also builds a solid foundation for understanding the area of specialized quantitative analysis—the basics for all common phases of environmental engineering. Requiring only a one-year college chemistry course, this book is suitable for advanced undergraduate and graduate level students of engineering and applied science. The presentation of the most current analytical procedures and latest concepts also makes it a valuable source of information for the professional engineer. Practice-oriented problems and worked examples help increase the reader's understanding of basic principles. 1978, 544 pages (tent.), \$19.50 (tent.) Solutions Manual available

## **Introduction to Polymer Processing**

Stanley Middleman, University of Massachusetts

Up-to-date and complete, this text offers a basic introduction to the methods of analysis of the major polymer flow and fabrication processes. The material is arranged to offer easier understanding by first developing the fundamental equations of heat and mass transfer, fluid dynamics, and rheology; then applying these equations to the development of models in a wide variety of polymer processes. End-of-chapter problems were selected to provide the experience of building, comparing, and evaluating models of varying complexity. 1977, 544 pages, \$25.00 Solutions Manual available

## **Introduction to Chemical Engineering**

Edward V. Thompson and William H. Ceckler, both of the University of Maine, Orono

This text introduces the student to the chemical process industry and its overall breadth while also developing strength in the analysis of material and energy balancing. The material is arranged around a series of analytical topics selected from important sectors of the chemical industry. Each topic is discussed by offering an introductory descriptive chapter followed by the necessary techniques and skills. Chemical principles, material balances, and energy balances are treated and developed simultaneously, with an early introduction to heat and enthalpy. 1977, 576 pages, \$19.50

## **Chemical and Catalytic Reaction Engineering**

James John Carberry, University of Notre Dame

Dr. Carberry's presentation embraces a diversity of heterogeneous reaction engineering phenomena. The text includes a discussion of homogeneous chemical reaction kinetics, followed by generalizations pertaining to ideal reactor types and their limiting environments. Following a treatment of real reactor equations and their parameters, heterogeneous reaction-reactor networks are analyzed.

1976, 704 pages, \$22.50

## **Unit Operations of Chemical Engineering, Third Edition**

Warren L. McCabe, Emeritus, North Carolina State University, and Julian C. Smith, Cornell University

Continuing in the tradition of the earlier, internationally acclaimed editions of this text, the third edition is a carefully integrated and balanced discussion of theory and practice. The revision now offers a thorough discussion of the three unit systems: FPS, CGS, and SI units; introduces fugacity and activity coefficients in the study of phase equilibria; and contains a completely new chapter on multi-component distillation. Other significant changes in the text include the extension of the Kwauk method for counting the number of independent variables in complicated separated operations; a thorough revision of the crystallization chapter to include recent work on contact nucleation; and additional material on mixing.

1976, 980 pages, \$24.00

## **Mass Transfer**

Thomas K. Sherwood, Robert L. Pigford, and Charles R. Wilke, all of the University of California at Berkeley

Providing broad coverage of mass transfer, this text emphasizes the practical aspects and real problems that demand an understanding of theory. Yet, theoretical derivations are minimized by explicit citation of over 1,100 contemporary references.

1975, 704 pages, \$22.50

prices subject to change

COLLEGE DIVISION  
McGraw-Hill BOOK COMPANY  
1221 Avenue of the Americas  
New York, N.Y. 10020



# A TELEPHONE TUTORIAL SERVICE

D. M. HIMMELBLAU  
*The University of Texas at Austin*  
*Austin, Texas 78712*

**T**HE TELEPHONE TUTORIAL program in the Chemical Engineering Department at The University of Texas is now in its twelfth year. It is possible to cite many individual cases of undergraduate students who have been helped through difficult periods in various courses with the aid of this service, and who have gone on to achieve an enviable record in their college work. Our tutorial activity supplies individual tutoring in the afternoons as well as a telephone tutoring service both in the afternoons and in the evenings.

I will first describe some of the reasons why the program was established and then explain the details of the program itself. For those interested in initiating a similar program I have included an explanation of how the tutors are chosen, how the work is handled by the tutors, and a description of the facilities and equipment. Some advantages and difficulties with the program will be discussed as well as the costs.

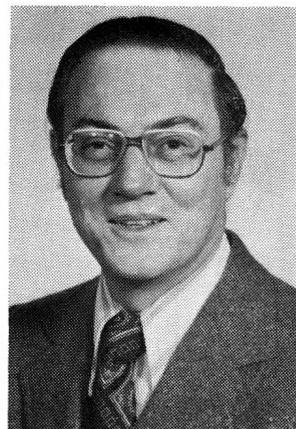
## REASONS FOR THE PROGRAM

**I**N ChE A STUDENT must understand a substantial number of basic concepts in the curriculum if he or she expects to progress satisfactorily. Any concept not fully understood at the time he or she first encounters it may continue to cause the student trouble as subsequent material is encountered. One way a student can get almost instant help is via an ongoing tutoring program.

Freshmen and sophomores particularly feel isolated from professors and other students at large universities, and they experience difficulty in obtaining help quickly when they flounder on a problem. Such a student is then likely not to learn what he or she should when he should. The Chemical Engineering tutoring program was established at The University of Texas to give

students who had to work alone, or found it convenient to work alone, or found it inconvenient to work with others, a chance to interact with another more advanced student on a problem of personal interest.

There were some additional reasons for establishing the tutorial program that are not so obvious. First, it is convincing evidence to our undergraduate students that we are sincerely interested in their difficulties. A student who has a difficulty in a course might first go to see the professor in charge of the course. On the other hand, the student may be slightly embarrassed to bother the professor but would not hesitate to see a tutor. Second, we have to admit with all due candor, that professors are busy individuals and



**Professor Himmelblau** received his B.S. degree from M.I.T. in 1947 and thereafter worked for the International Harvester Company of Chicago, the Simpson Logging Company in Washington, and the Excel Battery Company in Washington. He returned to school and received his Ph.D. from the University of Washington in 1957. Ever since then, he has been teaching at the University of Texas where he is now a Professor and Chairman of the Department of Chemical Engineering. He is a member of a large number of professional and honorary societies, has been a consultant for several companies, and has been quite active in the AIChE. He was a Director of the AIChE from 1973-76. He was on the Executive Committee of the Chemical Engineering Division of the ASEE from 1970-71, and on the Editorial Board of "Industrial and Engineering Chemistry Process Design" from 1972-75.

that students sometimes do not have the incentive, perseverance, or time to locate a professor at the time the question arises. Therefore, the fact that he knows a tutor is available four days a week and is available by telephone as well, makes the tutorial program a definite convenience.

It is interesting to note that some of the better students also take advantage of consulting a tutor in order to resolve questions and probe more deeply into the subject material.

### HOW THE PROGRAM OPERATES

LET ME NEXT EXPLAIN how the tutoring program is carried out. Every Monday, Wednesday, and Thursday afternoon from 3:00 to 5:00 p.m., and for variety, Tuesdays from

monthly or semester assignment sheets from those professors who hand out such sheets so that the tutors can prepare themselves for questions whenever they are momentarily unoccupied.

Some tutors prefer to help in certain courses, but all are sufficiently competent to tutor in any course. For increased efficiency often each tutor will answer all questions concerning one or two classes on a given day. However, the tutors continually change the classes they tutor to gain additional experience. Sometimes it takes all three tutors to answer a particularly difficult question.

If a student demonstrates that he or she has not seriously attempted to start the homework assignment or read the required material, the student is asked to return after doing so. This is done to prevent the tutoring program from be-

---

**A professor who wishes can use the tutoring program as a current and informal tool of teaching evaluation by finding the types and degree of difficulties students have with his classes. Also, an instructor if he goofs on an assignment, can leave a message concerning last minute changes in the homework assignments for the tutors to place on the tape.**

---

12:00-2:00 p.m., three tutors are available to help undergraduate chemical engineering students. Due to scheduling problems and lack of demand by students, the Friday session we used to have has been terminated. During these afternoon tutoring sessions, an average of twelve students are helped by calls or visits. The length of each student's visit varies from about a minute for a brief question to over an hour if he or she is thoroughly confused and does not even understand how to start the homework assignment. Most students find personal visits more effective than telephone inquiries for complicated problems so that our experience during the day is that only about ten percent of the tutoring contacts are via the telephone.

Tutoring takes place in a four hundred square foot seminar room. A large table is placed in the center around which are seats for up to fifteen students. An additional table at one side of the room holds the telephone and Code-a-phone. A large blackboard on one wall is used for explanations when four or more students from a particular class have the same questions. The tutors have access to a copy of the textbooks currently being used in all the required courses in the ChE curriculum. Every attempt is made to obtain

coming a problem work session, with the tutors assisting in working the homework assignments. We have recitation sections in many classes for such activities.

Any tutor who is free at the moment or closest to the telephone answers it. To provide help over the telephone is often difficult because the tutor often does not have the particular problem or text available at hand to read as does the student. Consequently, the tutor has difficulty in understanding what the student is asking. Even when the tutor understands the problem, he finds it more difficult to explain equations over the phone than it is to write them down and show them to the student directly. As a result, most students with long, involved questions visit the tutors in person, and the phone is used for brief questions.

### THE TUTORS AND THE CLIENTS

USUALLY FIVE individuals work in the tutorial program, but not all on the same day. One graduate student is placed in charge of the entire operation. He finds suitable tutors, coordinates tutoring activities, and sees that daily tapes are made. Explanations and hints to problems prepared one day by one group of tutors do not have to be redetermined on a succeeding day

because the head tutor is present every day. The remaining tutors each work only one or two days a week.

A good tutor needs to be patient, speak English well, be technically competent, and be relatively familiar with the assignments of the undergraduate courses. To meet the latter requirement it is best (but not essential) that the tutor have gone to undergraduate school where he tutors so that he has been in the classes of most of the professors. An academically qualified senior student best meets the requirements but may not have the maturity of a graduate student. Because many of the questions of ChE students relate to homework problems, we found it helpful to employ as tutors individuals who were graders in the sophomore and junior classes. These are the primary classes that cause students to come for help. The head tutor can also easily work with the class grader to give appropriate information to the students.

Although the tutors are available to answer questions concerning any of the undergraduate ChE courses, the bulk of the questions come from 4 or 5 sophomore and junior courses, particularly material and energy balances, transport phenomena, and unit operations. Hence, after one semester the tutors become fairly familiar with those classes that cause students the most problems, which increases the effectiveness of the tutoring.

#### TELEPHONE TUTORING

**I**N ADDITION TO tutors answering telephone calls in the day, we have an automatic telephone

---

**Our tutorial activity supplies individual tutoring in the afternoon as well as a telephone tutoring service both in the afternoon and in the evening.**

---

response in the evening. A Model 200-A "Code-a-phone" by Ford Industries, Inc. is connected to the tutorial telephone line. This machine can record up to six minutes of taped messages. It permits a student to listen to the recorded message but does not enable him to leave a message on the tape.

What bothers one student about an assignment usually bothers others. Consequently, students ask identical or related questions about ChE homework assignments due in the next day

or two. Because several students are likely to encounter the same difficulties, but for various reasons might not contact the tutors during the day session, a recorded message is prepared by the tutors at the end of each tutoring period. An extract of a typical message about one and one-half minutes in length is in the Appendix. This tape contains suggested approaches to homework assignments and discussions of difficulties that had caused the most questions during the tutoring proceedings of the day. Also included on the tapes are changes, corrections, or additions to homework assignments called in by the ChE instructors, and announcements by ChE organizations.

An average of one hundred fifty calls are received by the tape machine per night. (We get this information from a digital counter attached to the machine.)

#### IMPROVING THE SERVICE

**O**NE OF THE PROBLEMS a student faces in getting a message from the Code-a-phone is he must go through all of the message up to the point of interest. We examined different ways of having the student dial directly to his class number, but have not yet found any inexpensive equipment that would be suitable. In principle the introduction of such equipment would save a student the boring wait until his pertinent message came up on the tape.

At one time we thought we might make a tape available on which a student could leave a message to which a tutor could reply at some hour in the evening, but the demand for such a service was low. No one wished to stay home waiting for the reply. Several years ago we not only had the telephone service but also broadcast the tape over the student radio at 10:30 p.m. each day. Eventually the broadcast was stopped.

#### COSTS AND BENEFITS

**M**ANPOWER COSTS comprise the bulk of the operating costs of the tutoring program. One teaching assistant supervises the program and assists in the tutoring at a cost of \$2,200 per semester or about \$500 per month. In addition, about 4 seniors or graduate students are employed each for about 5 hours per week at a rate of \$4 to \$5 per hour, or another roughly \$2,000 per semester. The telephone rental is only \$16 per month or about \$200 per year, and the cost of the recorder has been written off long ago. In terms of the student visits, the cost is about \$3.50

per visit. However, in terms of visits plus telephone calls, the cost is less than \$1 per contact.

Our tutoring program has the usual benefits you might deem pertinent. It helps a student understand the class assignments as he goes along so that future material will be less difficult. This prevents a slow learner from getting too far behind his or her classmates. Some students at large universities are afraid to or are actively discouraged from asking their professors outside class about those small troubling questions that bother them. The tutoring program allows these students the satisfaction of getting their questions answered. The tutors also answer questions concerning the teaching style of a professor and what he stresses on exams. A professor who wishes can use the tutoring program as a current and informal tool of teaching evaluation by finding the types and degree of difficulties students have with his classes. Also, an instructor if he goofs on an assignment, can leave a message concerning last minute changes in the homework assignments for the tutors to place on the tape.

In addition to the primary benefits, some additional advantages exist because of the tutoring program. Undergraduates gain contact with upperclassmen, contact that they would not otherwise have. From this interaction they obtain informal advice concerning course scheduling, future job interviews, and graduate school. The tutoring program gives students an additional opportunity to meet each other outside of their classes. By getting to know other students they begin to help each other directly. We find seniors rarely use the tutoring service largely because by the time they become seniors they know many students in their classes and are therefore able to study with each other.

#### SOME DIFFICULTIES

**I**F THE STUDENTS who use the tutoring service are required to be prepared the best they can by themselves before they ask for help, the tutoring program does not make addicts of students. Such difficulties as exist tend to be operational.

Some students cannot find a spot in their schedules for a visit to the tutors because of time conflicts with other courses or outside work. Often the tutors are flooded with visits and frequently interrupted by telephone calls. On such days the tutors may not be as effective as they should be.

---

In addition to tutors answering  
telephone calls in the day, we have  
an automatic telephone response in the evening.

---

They often give quick answers rather than help the student get to the answer by indirect questioning. On other days, the tutors are not called on to help as many students as they could efficiently handle. Sometimes the tutors run into a question or problem that they cannot immediately answer because they do not have the proper background. In such cases the student is asked to return the next day in order to give the tutor time to check into the matter. A student is encouraged to see his professor in such circumstances.

But on the whole the program has been favorably accepted and widely used by an ever changing student population, and strongly supported by the faculty. □

#### APPENDIX

##### Example of Recorded Message Heard by Students During Non Tutoring Hours

Tonight the Chemical Engineering Tutoring Service will discuss ChE 317 problems 4.69 and 5.9, and Dr. Smith's section of ChE 322 problem number two. First, I would like to announce that there will be an AIChE meeting this Friday the thirteenth in the Geology Building, room number 100 at 4:00 p.m. The program will consist of a panel discussion with the Chemical Engineering Department Visiting Committee.

**ChE 317 Problem 4.69:** This is a review problem. Don't forget that you are supposed to work part b only. This problem is worked in a similar manner as example 4.33. Use equation 4.51 on page 301. Note that equation 4.51 is actually a special case of the general energy balance you used throughout chapter four when working heat of reaction problems.

**ChE 317 Problem 5.9:** For this problem use the enthalpy concentration chart for the sulfuric acid water system on page 463. Use the chart as shown in example 5.09 for the sodium hydroxide water system. This problem is of the mass and energy balance type you have had many times before and is used merely to illustrate use of enthalpy concentration charts.

**ChE 322:** This is a multistage adiabatic compressor problem. There is intercooling between each stage and a 5 psi pressure drop in each intercooler. Equation 78 on page 674 should be used since the gas temperature entering each stage is the same and each stage may be assumed to have the same compression ratio. For a given number of stages, calculate the total work required. Then guess a different number of stages and again calculate the total work required. A plot of total work required as a function of compressor stages is used to determine the desired number of stages and hence the operating costs of the system.

# TAKE TWO PILLS EVERY FOUR HOURS: A Hydrodynamic Analog For Drug Dosage Regimens

SCOTT C. JACKSON AND  
JAMES F. STEVENSON  
*Cornell University  
Ithaca, NY 14853*

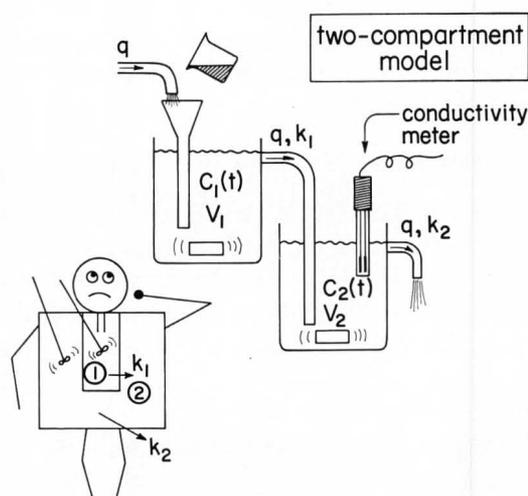
**T**HE EVERYDAY EXPERIENCE OF taking a drug orally at prescribed time intervals is the basis for the mathematical analysis and experimental demonstration described here. A two-compartment stirred-tank model is used as a lumped-parameter model for the human body. This mathematical model was presented in a junior-level course at Cornell titled "Engineering Analysis of Physiological Systems" and the demonstration was used with student participation during open houses. The preparation of a videotape recording of the mathematical analysis and the experiment is currently being planned for a sophomore-level mathematics course.

## TWO-COMPARTMENT MODEL

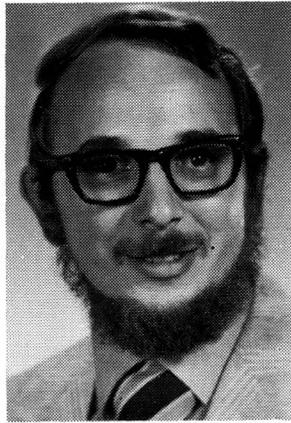
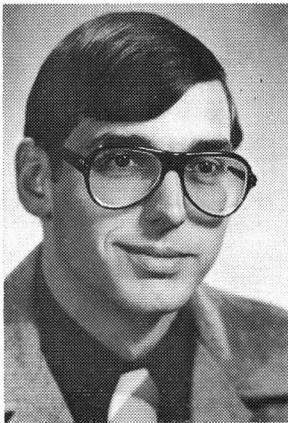
**A** SCHEMATIC DRAWING of the two-compartment hydrodynamic model is shown in Figure 1. The first tank with uniform concentration  $C_1$  stands for the gastrointestinal tract from which the drug is absorbed into the rest of the body (blood, muscles, tissues, etc) represented by the second tank. Oral ingestion of the drug is represented by pouring specified amounts of the drug analog into the first tank at prescribed time intervals. The rate of absorption from the gastrointestinal tract is linearly related through the proportionality constant  $k_1$  to the time-dependent drug concentration in the tract  $C_1(t)$ . The hydrodynamic analog of absorption is the volumetric flow rate  $q$  between the first and second tanks. The drug is eliminated from the rest

of the body through the kidneys at a rate  $k_2 C_2(t)$  where  $C_2(t)$ , the concentration in the second tank, stands for the drug concentration circulating in the body. Elimination is represented by the exit stream from the second tank.

In order for the drug to be safe and effective, the concentration level in the body  $C_2$  must be maintained above the minimum effective concentration  $C_{2min}$  but below the toxic concentration,  $C_{2max}$ . By specifying the initial and subsequent maintenance doses,  $m_i$  and  $m_m$ , and the time intervals following the initial and maintenance doses,  $T_i$  and  $T_m$ , a concentration plateau can be achieved in which the concentration  $C_2(t)$  never drops below the minimum effective concentration  $C_{2min}$  after the initial time interval and never exceeds the toxic concentration  $C_{2max}$ . Although this model is a relatively simple representation of



**FIGURE 1.** Schematic drawing of the two compartment model and a reluctant "dosee."



**Scott C. Jackson** received his BSChE from Cornell University (1977) and is currently a graduate student in the Chemical Engineering Department at the University of Delaware. Scott is an avid photographer, bicyclist and humorist with a fine sense of the absurd. (L)

**James F. Stevenson** received his BSChE from Rensselaer Polytechnic Institute and his MS and PhD degrees from the University of Wisconsin. He is currently an associate professor in the School of Chemical Engineering at Cornell University. His research interests include polymer rheology and processing and mass transport in membranes. (R)

a complex process, it does illustrate the general features of drug distribution kinetics.

### MATHEMATICAL DESCRIPTION

THE ANALYSIS GIVEN below has been adapted from a paper by Buell *et al.* [1]. Mass balance on the two stirred tanks give the following governing equations:

$$\frac{dC_1}{dt} = -kC_1 \quad (1)$$

and

$$\frac{dC_2}{dt} = kC_1 - kC_2 \quad (2)$$

where for convenience we have specified that the volumes of well-stirred liquid in the tanks are equal,  $V_1 = V_2 = V$ , so that  $k_1 = k_2 = K = q/V$ . Prior to time  $t = 0$ , the stirred tanks contain no drug and at  $t = 0$  the initial dose  $m_i$  is administered to the first stirred tank. An instant later at  $t = 0^+$ , the initial concentrations are

$$C_1(0^+) = m_i/V$$

and

$$C_2(0^+) = 0. \quad (3)$$

A periodic condition  $C_1$  is that the concentration of drug in the first stirred tank just prior to a maintenance dose  $C_1(T_i + nT_m^-)$  plus the increase

in concentration due to the maintenance dose  $m_m/V$  is equal to the concentration in the first stirred tank just after the maintenance dose  $C_1(T_i + nT_m^+)$  or

$$C_1(T_i + nT_m^-) + m_m/V = C_1(T_i + nT_m^+) \quad (4)$$

where

$$n = 0, 1, 2, 3, \dots N.$$

To achieve the plateau effect mentioned previously the concentration at the end of the initial time interval  $C_2(T_i)$  must be equal to the concentration at the end of all of the maintenance time intervals  $C_2(T_i + nT_m)$  or

$$C_2(T_i) = C_2(T_i + nT_m) \quad n = 1, 2 \dots N. \quad (5)$$

A similar condition also applies to the first tank (1):

$$C_1(T_i^-) = C_1(T_i + nT_m^-) \quad n = 1, 2 \dots N. \quad (6)$$

General solutions to the above system of equations have been given by Buell *et al.* (1). The solu-

**In order for the drug to be safe and effective the concentration level in the body  $C_2$  must be maintained above the minimum effective concentration  $C_{2min}$  but below the toxic concentration  $C_{2max}$ .**

tions for the special case considered here are as follows:

For the initial time interval,  $0 \leq t \leq T_i$ ,

$$C_1(t) = (m_i/V) \exp[-kt] \quad (7)$$

and

$$C_2(t) = (m_i/V) kt \exp[-kt] \quad (8)$$

For the maintenance time intervals,

$$T_i + nT_m^+ \leq t \leq T_i + (n+1)T_m^-,$$

$$C_1(t) = [C_1(T_i + nT_m^-) + (m_m/V) \exp[-k(t - T_i - nT_m)]] \quad (9)$$

and

$$C_2(t) = C_2(T_i + nT_m) \exp[-k(t - T_i - nT_m)] + [C_1(T_i + nT_m^-) + m_m/V] [k(t - T_i - nT_m)] \exp[-k(t - T_i - nT_m)]. \quad (10)$$

The results given above can be used to obtain the following relations among the parameters  $T_i$ ,  $T_m$ ,  $m_i$ ,  $m_m$ ,  $C_{2min}$  and  $C_{2max}$ :

$$\frac{T_i}{T_m} = \frac{1}{1 - \exp[-kT_m]} \quad (11)$$

$$\frac{m_i}{m_m} = \frac{\exp[kT_i]}{\exp[kT_m] - 1} \quad (12)$$

$$\frac{m_i}{VC_{2min}} = \frac{\exp[kT_i]}{kT_i} \quad (13)$$

and

$$\frac{C_{2max}}{C_{2min}} = \frac{\exp[kT_i] - 1}{kT_i} \quad (14)$$

It can be shown that, in general, the maximum concentration in the second tank during the initial time interval is equal the maximum concentration during the maintenance intervals.

Eqs. (11) — (14) place four restrictions on the six parameters  $T_1$ ,  $T_m$ ,  $m_i$ ,  $m_m$ ,  $C_{2min}$  and  $C_{2max}$ . At most, two of these parameters can be specified at will. For example, if  $T_m$  and  $C_{2min}$  are specified, then  $T_1$  is calculated using Eq. (11),  $m_i$  and  $m_m$  are determined from Eqs. (13) and (12) in that order.  $C_{2max}$  is given by Eq. (14).

## EXPERIMENTAL PROCEDURE

AS SHOWN IN FIGURE 1, the experimental apparatus consists of two stirred tanks holding equal volumes and connected in series with a short piece of large diameter tubing. At the appropriate times the prescribed amounts of drug analog, sodium chloride, are poured rapidly into the first tank through the funnel. To achieve rapid, uniform mixing, the tube carrying the inflow stream for each tank ends in a region adjacent to the magnetic stirrer. The entrance of the outflow tube is located as far away as possible from the magnetic stirrer. The concentration in the second tank is measured continuously using a conductivity meter.

A convenient method for setting the parameters is outlined below. During the initial dose interval, the maximum concentration in the second tank  $C_{2max}$  occurs at the time  $T_{max} = 1/k$  (1). Using the value for  $k$  determined by this method, one can specify  $T_m$  to be

$$T_m = 1/k \quad (15)$$

and from Eq. (11) obtain the result

$$T_1 = 1.5812 T_m \quad (16)$$

Next  $C_{2min}$  can be specified and Eq. (13) used to determine

$$m_i/V = 3.074 C_{2min} \quad (17)$$

From Eq. (12)

$$m_i = 2.829 m_m \quad (18)$$

Finally  $C_{2max}$  during the maintenance and initial intervals is determined from Eq. (14) to be

$$C_{2max} = 1.131 C_{min} \quad (19)$$

An experimentally measured trace  $C_2(t)$  is shown in Figure 2. For this experiment  $q = 11.6$  ml/sec and  $V = 310$  ml not including the small volumes in the connecting tubing. The experimentally measured value of  $k = 1/T_{max} =$

$0.0370 \text{ sec}^{-1}$  is in close agreement with the predicted value  $k = V/q = 0.0374 \text{ sec}^{-1}$ . Setting  $T_m = 1/k = 27 \text{ sec}$  and  $C_{2min} = 0.0379 \text{ moles/l}$ , we obtain  $T_1 = 43 \text{ sec}$ ,  $m_i = 0.0361 \text{ moles}$ ,  $m_m = 0.0128 \text{ moles}$  and  $C_{2max} = 0.0429 \text{ moles/l}$  using Eqs. (15) — (19). These parameters were used to obtain the experimental results shown in Figure 2 except  $m_m$  was increased to 0.0138 moles. This adjustment in  $m_m$  was necessary to obtain the nearly uniform minimum values for  $C_2(t)$  shown in Figure 2. The increase in  $m_m$  and the fact that

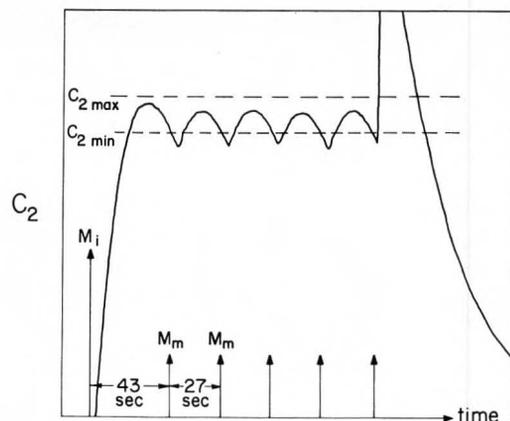


FIGURE 2. Graph of  $C_2$  vs. time. Arrows along the time axis indicate the intervals and relative amounts for the drug doses. The last peak represents the response when the dose  $m_m$  is injected directly into the second tank.

the measured  $C_2(t)$  values fall slightly below their predicted maximum and minimum values are probably caused by less-than-perfect mixing in the tanks and the unmixed volumes in the connecting tubing. Note that these effects also cause a 3-4 second lag time between the administration of the maintenance dose and the minimum in the  $C_2(t)$  curve. The last peak in the  $C_2(t)$  trace in Figure 2 represents the response of the system to a direct injection of  $m_m$  into the second tank.

Some precautions necessary to insure good results in this experiment are accurate measurements of  $m_i$ ,  $m_m$ ,  $T_1$  and  $T_m$  and care in constructing the hydrodynamic analog so that it will correspond as closely as possible to the idealized two-compartment model. □

## ACKNOWLEDGMENT

The authors wish to acknowledge Professor K. B. Bischoff, Neal Zislin and Charles Baker for their contributions to this project.

## REFERENCES

- Buell, J., R. Jelliffe, R. Kalaba, and R. Sridhar, *Math. Biosci.*, 5, 285 (1969).

# THE ROAD TO HELL

KARL ZIPF

Carnegie-Mellon University  
Pittsburgh, Pennsylvania 15213

*In the course of their education, chemical engineers probably work enough homework problems to pave the road. The following question was assigned by S. L. Rosen to the New Alternative students this past summer.*

*Prove that Hell is isothermal.*

*This proof requires two assumptions, both probably pretty good:*

- a) *There are some capable engineers among the inhabitants.*
- b) *They are suffering as much as the other lost souls.*

*The expected answer involved the concept that a heat engine can always be run between two reservoirs at different temperatures. Therefore, if Hell were not isothermal, the engineers could build engines to run air conditioners, shovel coal into the fires, etc.*

*However, Karl Zipf's answer showed a good deal more originality. It follows here:*

**G**O TO HELL. Yes, this is probably the easiest way to prove whether Hell is isothermal or not. All one has to do is record some meaningful data. However, I shall try to prove or disprove it without undertaking the journey.

$$PV = nRT \quad (1)$$

One can use the above equation for the basis of the proof, but first the theological problem of how many moles to a soul must be solved. If the soul is a physically real item\* then it will have a molar mass. Thus over a period of time there should be an increase in the souls in Hell, and therefore, an increase in the number of moles in Hell. This assumption can be readily proven by the fact that the population has been increasing.

\*There are indications that the soul is physically real and is a vapor.

A further assumption is that the ratio of good: bad has remained constant. However, some denominations believe that if one does not subscribe to their doctrine then one is going to Hell. These sects often mutually exclude each other and there could be the possibility that everyone is going to Hell. Regardless of the exact numbers involved it is apparent that the overall number of souls in Hell is on an increase. Since the population of Hell is parallel to the population of Earth, then the general trend in Hell can be seen as a rapidly increasing exponential population.

Lastly, it can be concluded that the volume of Hell has remained constant, since Hell has not manifested itself upon the Earth, contrary to popular belief.

Now let us review the two assumptions.

- 1) There is an increase in the number of the moles of souls in Hell.
- 2) The volume of Hell is constant.

Upon rewriting Eq. (1) :

$$\Delta \left( \frac{P}{T} \right) = \frac{\Delta nR}{V} \quad (2)$$

As one can see that as the moles of souls increase the  $\Delta P$  increases or  $\Delta T$  decreases. If the pressure increased, then there could eventually be an explosion, and then all Hell would break loose. Because this has not happened it can be assumed that the pressure is constant and that the temperature must decrease. Thus, Hell is not isothermal. Furthermore, the decrease in temperature supports Dante's observations, for according to his data the center of Hell is a frozen lake.  $\square$

FINIS

Karl Zipf

MCMLXXVI Anno Domini

---

Karl Zipf is a single, male student in the Department of Chemical Engineering at CMU. He is finishing an M.S. thesis on Soil Stabilization with Professor Rosen this semester. He is 24. Karl has a B.S. in Biology from Lehigh University and is one of our second year New Alternative graduates.

---

## THERMODYNAMIC HERESIES

M. V. SUSSMAN  
 Tufts University,  
 Medford, Mass. 02155

### *Heresy: A False and Misleading Doctrine Subversive of Accepted Principles*

- I "ENERGY IS THE ABILITY TO DO WORK"
- II "IF  $\Delta G_{\text{reaction}}$  IS POSITIVE, THE REACTION DOES NOT GO"
- III " $dU = TdS - PdV$ , FOR A REVERSIBLE PROCESS"

ASK ANY THERMODYNAMICS class, anywhere, for: a) a definition of energy; b) the significance of  $\Delta G > 0$ ; c) the process limitations  $dU = TdS - PdV$ , and with unfailing regularity the three lead statements will be forthcoming. Usually the more reticent the class, the stronger their conviction, that these at least are truths they have mastered.

---

Should there be some among the multitudinous readership who feel that stronger remedies of a more metaphysical nature, are needed to dispel the doctrines here condemned, I have in my files a copy of the exorcism formula, pronounced prior to hanging, against the murderers of the Archbishop of Dublin . . . adapted for use on thermoheretics.

---

Yet the lead statements are at best misleading, and at worst, false. They are thermodynamic heresies that are universally held. It is time to banish these misleading ideas from the company and discourse of the elevated and learned, by

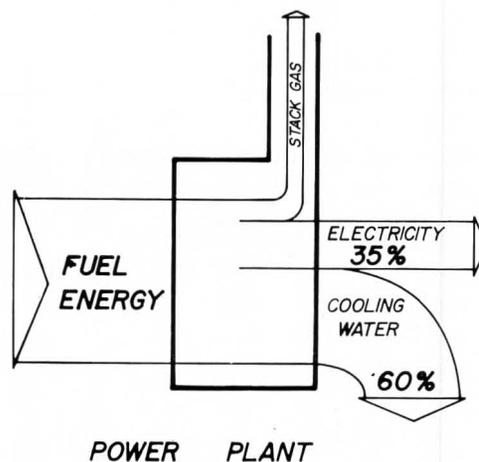


FIG. 1. Energy Flow in Power Plant.

which I of course mean chemical engineers. In lieu of Bell, Book and Candle, I will attempt to exorcise them by examining each so closely that its inherent misrepresentation stands revealed.

### HERESY I "Energy is the Ability to do Work"

If only it were. The operation of a modern plant would then be radically changed. Instead of having energy flows such as those shown in Figure (1) where most of the incoming energy leaves with the condenser waste water and only 35% is converted into electricity (work), we would have the electric energy (work) output of the power plant equal to that of the fuel energy input. But not only does most of the energy escape in the condenser cooling waters, these torrents of energy usually have negative work ability because work must be done to dispose of them properly.

Were statement I true there could never be an "energy shortage" because energy is always conserved. The air, sea, and earth are full of energy. No matter how many power plants, automobiles, air conditioners, steel mills, etc. we build, the

energy stores are not reduced because energy is *never* destroyed.

"The ability to do work," however, is easily destroyed and terribly fragile. It is easily consumed, and frequently is destroyed without ever fulfilling its work potential. The proper appellation for this fragile property is "*availability*," or available energy." Availability, not energy, is the measure of the "ability to do work." The "availability shortage" and not "energy shortage" is and will be a permanent and growing problem of industrial society.

The question of the definition of energy raised in the opening paragraph is perhaps an unfair one to spring on an unprepared class because energy is a difficult and subtle concept whose adequate definition goes well beyond the purpose of this paper. Suffice it to say that Energy is: that which is always conserved in all processes; that which manifests itself as heat or work when crossing the boundaries of a closed system; and that whose accumulation within a system is altered to an extent exactly equal to the net mass, heat, and work interchanges that the system has with its surroundings. The "ability to do work" it is *not*.

## HERESY II

"If  $\Delta G_{\text{reaction}}$  is Positive, the Reaction Does Not Go"

**T**HIS IS THE MOST prevalent, misleading, and insidious heresy on our list. It is taught as catechism in chemistry courses the world over yet it is at best a half truth. If it were true, major parts of the chemical industry would not operate. There would be no cracking or reforming plants. Methanol would not be synthesizable from CO and H<sub>2</sub>.

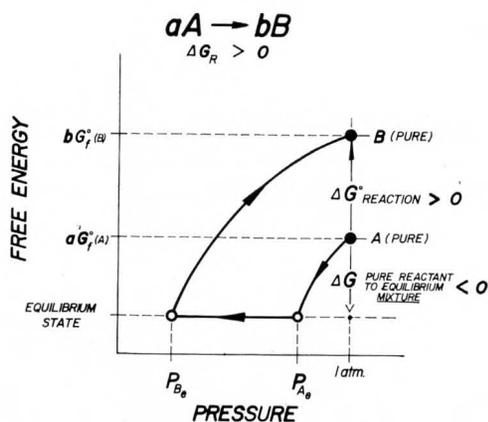


FIG. 2. Path for Reaction Free Energy Change.

WINTER 1978



M. V. Sussman of Tufts University was a reasonable facsimile of the above photo, in an earlier edition. His thermodynamic thoughts have graced this journal previously ("Seeing Entropy, or the Incomplete Thermodynamics of the Maxwell Demon Bottle", p. 149-156, Summer 1974; "Approaches to Statistical Thermodynamics", p. 40, 49, Summer 1968 and may be found in full measure in "Elementary General Thermodynamics", Addison-Wesley, a book featuring full page photos of Thermodynamic's "All-Time'All-Stars" and a method for out-maneuvering Maxwell's Relations."

What then, is significance of  $\Delta G_r > 0$ ? The  $\Delta G_r$  is the free energy change that accompanies the conversion of *pure* reactants to *pure* products at a specified temperature and total pressure.

For example for the gaseous reaction: A (pure, at T and P)  $\rightarrow$  B (pure, at T and P) the computation path for the free energy change of reaction may be represented as in Figure 2, where the total pressure is taken to be 1 atmosphere. To evaluate  $\Delta G_r$ , we sum the free energy changes along path A-pA-pB-B. A free energy loss occurs as A expands to its partial pressure  $p_{A_e}$  in an equilibrium reaction mixture of A + B. No free energy expenditure is needed to convert A at  $p_{A_e}$  to B at its equilibrium concentration ( $p_{B_e}$ ). But the free energy of B must be increased to concentrate it from  $p_{B_e}$  to P.

The total change for the process is the sum of the  $\int VdP$  from A to  $P_{A_e}$ ,  $P_{A_e}$  to  $P_{B_e}$  to B, and is equal to  $\Delta G^o_{\text{reaction}}$ . When we sum these integrals we obtain the familiar result

$$\Delta G^o_r = -RT \ln \frac{p_{B_e}}{p_{A_e}}$$

$$\Delta G^o_r = -RT \ln K$$

for any reaction.

Now  $\Delta G_r$  is shown as positive in Figure 2. Does this mean, "The reaction does not go"? Clearly it does not. The positive value of  $\Delta G^o_r$  simply indicates that the concentration of product in the equilibrium mixture is less that of reactant,

or that  $K$  in equation (2) is less than 1. Were we to use this reaction to produce  $B$ , the equilibrium mixture leaving the reactor would contain less  $B$  than  $A$ , and consequently would need to be separated into its components, with the unreacted  $A$  being recycled to the reactor. Notice that the free energy change in moving pure reactant to the *equilibrium state* is *negative* even when the overall  $\Delta G^\circ_r$  is positive. Therefore *the reaction always goes to its equilibrium state*. If  $\Delta G^\circ_r$  is positive the concentration of product in the equilibrium reaction mixture is low and insufficient to make  $K > 1$ . Of course if  $K \ll 1$  this concentration may be so low as to be insignificant, as for example in the decomposition of water to hydrogen and oxygen at room temperature. On the other hand as  $K \rightarrow 1$ , for valuable or easily isolated products, the product concentration may be large enough to make cleaning up the equilibrium mixture worthwhile.

### HERESY III

**" $dU = TdS - PdV$  For A Reversible Process (in a simple system)"**

The statement is indisputable but only because it is a tautology. You can say with equal validity:

$dU = TdS - PdV$ , in Paris in the Spring;

or, on Tuesdays or Fridays;

or, for an *irreversible* process

I consider it heresy because it implies to too many students that  $dU$ , a differential of a property, is dependent on process or path, and is otherwise defined for an irreversible process.

Statement III should never stand alone, though it does all too frequently in many respected texts. Better still to avoid it completely or replace it with the following:

For *any* process, reversible or irreversible, that moves a simple system from one equilibrium state to another, the internal energy change may be evaluated by integrating:

$$dU = TdS - PdV$$

along any reversible path that interconnects the terminal states of the process.

I have discoursed briefly on some old, treasured and well rooted thermodynamic prejudices. Should there be some among the multitudinous readership who feel that stronger remedies of a more metaphysical nature, are needed to dispel the doctrines here condemned, I have in my files a copy of the exorcism formula, pronounced prior to hanging, against the murderers of the Arch-

bishop of Dublin, in 1534, and adapted for use on thermoheretics. This I will be glad to send to the initiated in unmarked brown envelopes upon request.  $\square$

### ChE EDUCATOR: Scott Fogler

Continued from page 7.

Scott's daughter, Kristin, age 6, was quick to feel left out from the Indian Guides activities. Scott realized that there wasn't a similar activity for young girls in Ann Arbor. At Kristin's urging, he organized a council of "Indian Princesses" in Ann Arbor. Scott was the first Nation Chief of the Indian Princesses. He's been a successful Chief: In the first year there were five tribes with a total of about 50 fathers and daughters.

Peter, age 11, got Scott involved in another after-hours effort: Little League. When Peter's 5th grade class couldn't find a willing coach, Scott stepped in to lead the team to a 1 and 9 record for the season, which doesn't speak too well for the ability of the team (or coach?). But, imagine keeping eighteen 10-year-olds interested enough to keep playing ball even though they were losing all the time! That takes real dedication and understanding.

Jan, Scott's wife, is also involved in teaching as she has 25 piano students and currently serves as president of the Ann Arbor Area Teachers' Guild.

In his few leisure moments, Scott spends some time gardening. He finds Michigan a frustrating place to raise plants because of its hard clay soil. He plants three trees for each one that lives.

The whole Fogler family shares an enthusiasm for travel, and Scott has lectured in Scandanavia, Italy, South America, and Mexico City. Whenever he travels, he takes along his programmed-learning text. He has a file of slides which show him reading the text in front of landmarks such as the Tower of Pisa. He uses the slides as visual one-liners during his lectures.

Scott Fogler loves teaching, loves research and approaches them both with unbounded energy. He is perhaps his own best example of creative synthesis. He has developed his teaching skills and mixed them with humor to produce memorable classes for his students. He has used some bit of educational theory and his own creativity to gain recognition as an outstanding educator. As he says: "A little theory is very practical!"  $\square$

**STATISTICAL METHODS FOR ENGINEERS AND SCIENTISTS**

By Robert M. Bethea, Benjamin S. Duran and Thomas L. Boullion

Marcel Dekker, Inc., 1975. 583 pages.

Reviewed by Richard W. Mensing,  
Iowa State University

Anyone writing a book on statistical methods for engineers is confronted with a decision about what statistical topics to include in the book. There are many areas of engineering and the most applicable statistical methods are not the same for all groups. For example, industrial, traffic and electrical engineers frequently use probability modeling as a tool in analysis. Thus, the most applicable statistical methods for these engineers includes estimation, tests of goodness of fit, regression analysis, and statistical analysis of data taken over time. Reliability is a topic of principle concern to nuclear and mechanical engineers so life test data, statistical analysis of exponential, Weibull and lognormal data and propagation of errors are of utmost importance to this group. On the other hand, chemical, sanitary and materials engineers are often concerned with experimental data and thus make heavy use of regression analysis and the analysis of variance. The authors of this book address themselves to the latter group of engineers and as such cover most of the usual topics which would be introduced in a first course in statistical methods for these engineers.

After a brief introduction, Chapter 2 introduces the basic concepts of probability. This is followed by a chapter on distributions. Included in this chapter are both experimental distributions (as usually derived from sample data) and theoretical or probability distributions. The notion of the mean and variance of a probability distribution is also introduced in this chapter. Expected values and moments are again covered in Chapter 5 along with joint probability distributions and the independence of random variables. These chapters represent the introductory background material on probability. Chapter 4 covers descriptive statistics. Basic statistical inference is the topic of Chapters 6 and 7. Estimation is covered in Chapter 6. Also introduced in this chapter are

three sampling distributions, the  $t$ ,  $X^2$  and  $F$  distributions. Chapter 7 covers the usual tests of hypotheses about means, variances and proportions. The method of the analysis of variance is introduced in Chapter 8 as a method of comparing several normal populations. One, two and three way analyses of variance are covered. Also, Bartlett's test for comparing several variances is discussed in Chapter 8. Regression analysis, including simple linear, multiple linear, polynomial and nonlinear regression is the topic of Chapter 9. A separate chapter, Chapter 10, is devoted to orthogonal polynomials. The final chapter is on experimental design and covers the analysis of variance associated with completely randomized, randomized complete block, latin square and split plot designs. Factorial experiments are also discussed in this chapter.

In considering this book as a textbook for an introductory course in statistical methods for engineers and scientists, I believe it has several drawbacks. For one, there are several places where I think the book is too terse, particularly in introductory sections and sections on definitions. For example, in Chapter 3 on distributions, a random variable is defined as "a function from a sample space to the real line" with no further discussion. I do not believe this brief definition is enough for someone encountering this concept for the first time to really understand what a random variable is and what its importance is in statistics. Also, populations and a sample (defined as "part of a population") are only defined, but, although it is used throughout the book, there is no discussion of a *random* sample. In Chapter 11, much of the terminology surrounding experimental design (e.g. treatments, experimental units, experimental error, factors, etc.) are only *briefly* defined with only a minimal amount of discussion. This certainly would have to be supplemented by the instructor for a student to gain an understanding of these terms. On the other hand, for a methods book, I believe the authors go into too much theory on some topics. This is particularly true in Chapter 5 on expected values where there are several derivations which are unnecessary.

The authors mention that the book is intended for undergraduate students in engineering and the physical sciences. I believe the students should be upper level undergraduate or beginning graduate students. A two-quarter course which

Continued on page 46.

# USE AND ABUSE OF EFFICIENCIES IN SEPARATION PROCESSES

A. A. H. DRINKENBURG  
University of Groningen,  
Groningen, the Netherlands

In two phase separation processes often confusion arises about the meaning and definition of stage-contact-efficiencies. The efficiency, sometimes erratically, is considered to be a measure of the purification obtained in the process under study or in part of it. Moreover, there are many ways to define an efficiency e.g. the Murphree plate efficiency based on the vapor feed or on the liquid feed, a Hausen efficiency and a point efficiency. In this paper we will look shortly into the difference between degree of purification and efficiency and elaborate somewhat further upon the physical meaning of the efficiencies, as normally used in literature.

Most separation processes can be shown to be built-up from units in which two flows make physical contact and thereby exchange part of their components, or heat. For simplicity's sake let us first suppose that one feed,  $F$ , is introduced and that two flows,  $L$  and  $V$ , leave the unit. A component, called  $A$ , has to be separated in purified form. All other components are taken together, as  $B$ . The composition of the flows is then  $x_A$  resp.  $x_B$ .  $x_A$ ,  $x_B$  and  $F$ ,  $V$  and  $L$  must be taken in consistent units, e.g. concentrations in mole fractions and flows in mol/s. Or flows in kg/s and concentrations in weight fractions.

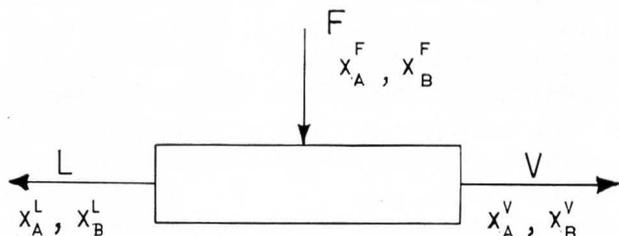


FIGURE 1. Process with one inlet and two outlets.

Now the degree of purification can be defined as

$$P = \left| \frac{L \times \frac{L}{A}}{F \times \frac{F}{A}} - \frac{L \times \frac{L}{B}}{F \times \frac{F}{B}} \right| = \left| \frac{V \times \frac{V}{A}}{F \times \frac{F}{A}} - \frac{V \times \frac{V}{B}}{F \times \frac{F}{B}} \right| \quad (1)$$

Note that this expression has the advantage that the degree of purification remains the same, irrespective 1) which outlet stream ( $L$  or  $V$ ) is taken into consideration and 2) whether com-

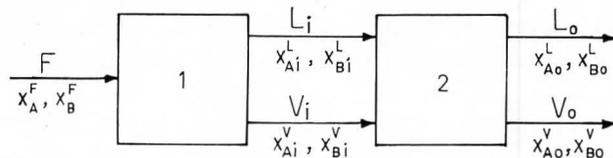
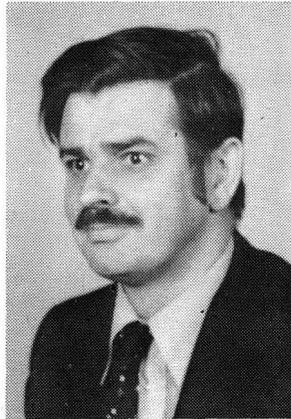


FIGURE 2. Two phase separation process.

ponent  $A$  or the sum of all other components,  $B$ , is considered.

Also important is that  $P$  will always have a value between 0 and 1, zero if the flows  $L$  and  $V$  have the same composition as flow  $F$ , thus when no separation has actually taken place and one if the two components  $A$  and  $B$  are completely separated.

The expression for  $P$  was originally introduced for cyclones [1]. In many cases the feed entering the separation unit is in itself split up into two flows, for example when a stage of a counter-current separation process is considered. Now the incoming flows may be taken as those leaving an imaginary process (drawn on the left in figure 2, marked with the number 1), which is fed by  $F$ . This means that the incoming flows in the actual



**Bart Drinkenburg** received his engineers degree and Ph.D. from the Technological University of Eindhoven, the Netherlands. He spent one academic course teaching at the University of London and thereafter joined the University of Groningen, the Netherlands, to become an associate professor in chemical engineering. His main field of interest in research is two-phase flow and mass transfer in packed columns, including trickle bed reactors.

piece of equipment on the right 2, already have a degree of purification:

$$P_{in} = \left| \frac{V_i x_{Ai}}{F x_A} - \frac{V_i x_{Bi}}{F x_B} \right|$$

$$= \left| \frac{V_i x_{Ai}}{L_i x_{Ai} + V_i x_{Ai}} - \frac{V_i x_{Bi}}{L_i x_{Bi} + V_i x_{Bi}} \right| \quad (2)$$

The flows leaving the actual equipment, 2, have a degree of purification

$$P_{out} = \left| \frac{V_o x_{Ao}}{L_i x_{Ai} + V_i x_{Ai}} - \frac{V_o x_{Bo}}{L_i x_{Bi} + V_i x_{Bi}} \right| \quad (3)$$

We expect, as a result of the contacting process, that the degree of purification will increase,  $P_{out} > P_{in}$ . Its difference,  $\Delta P$ , is the working of the piece of equipment under study:

$$\Delta P = \left| \frac{V_o x_{Ao} - V_i x_{Ai}}{L_i x_{Ai} + V_i x_{Ai}} - \frac{V_o x_{Bo} - V_i x_{Bi}}{L_i x_{Bi} + V_i x_{Bi}} \right| \quad (4)$$

It is this number,  $\Delta P$ , in which the process engineer will be interested when he compares alter-

natives for separation.

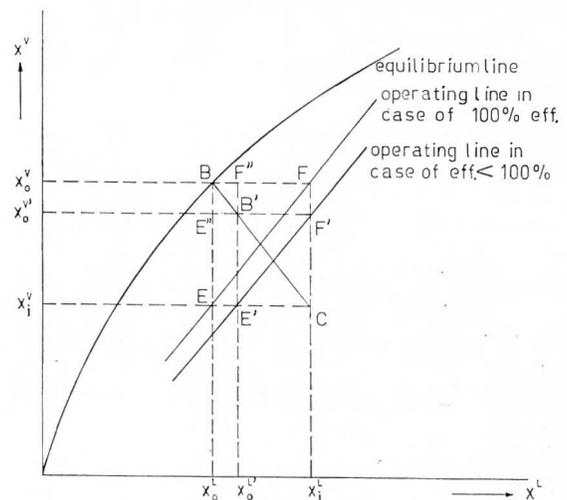
Note that, until now, nothing has to be known about the contacting process itself. The only tool used a *mass balance* over the equipment, or part of it.

### CONTACTING STAGE EFFICIENCY

**I**N MANY CONTACTING processes the equipment not necessarily has to be considered to be a black box. Contacting stages are so devised that the flows leaving the stages are more or less in physical equilibrium. This means that besides the mass balance an *equilibrium relationship* comes into the picture. A theoretical stage (theoretical plate) is a part of the equipment where the outgoing flows are in physical equilibrium. Its efficiency is taken to be 100%. However, the outgoing flows from practical stages are seldomly in equilibrium and then a problem arises. The efficiency of the stage then has to be expressed into flows and concentrations. The definition of the efficiency is often ambiguous as we will see. For only one definition, the efficiency can be shown to be consistent with the defined degree of purification.

The relation between the effects of a theoretical stage and a practical stage is elucidated by means of a graphical representation, figure 3.

Point C represents the compositions of the flows L and V entering the contacting stage. We took it that L and V do not change during the contacting process, a condition that is appropriate in many practical circumstances and in many other circumstances can be made appropriate by



**FIGURE 3. Composition diagram. Action of a contacting stage.**

choosing suitable units to express  $L$  and  $V$ .

Line CB then represents the mass balance for component A, since

$$L \cdot x_{Ai}^L + V \cdot x_{Ai}^V = L \cdot x_{AO}^L + V \cdot x_{AO}^V$$

and therefore

$$x_{AO}^V - x_{Ai}^V = -\frac{L}{V} [x_{AO}^L - x_{Ai}^L]$$

In the following the subscript A will be omitted since everywhere  $x$  will represent the concentration of A in the flow under study.

For a 100% efficiency, point B on the equilibrium line gives the compositions of the two flows leaving a theoretical contacting stage. Point F and E, as is well known, then represent the concentrations of A in the flows that pass each other in between the contacting stages in a multiple-stage-counter-current contacting process and are points of the so called operating line. The slope of the operating line has the opposite sign as the slope of the above mentioned mass balance plot:

$\frac{L}{V}$ , the flow ratio of the two contacting phases.

In case the state of equilibrium is not reached, the concentrations of the flows leaving the practical stage are not given by B, but the process stops somewhere on the line CB, e.g. B' and consequently the operating line will shift to E'F'.

When we wish to compare the performance of the practical contacting stage to that of a theoretical one it is logical to relate its degree of purification to that of a theoretical stage and therefore we now express its efficiency as:

$$E = \frac{\Delta P_{\text{practical stage}}}{\Delta P_{\text{theoretical stage}}} = \frac{P_{\text{practical out}} - P_{\text{in}}}{P_{\text{theor. out}} - P_{\text{in}}}$$

If  $L/V$  is constant then:

$$E = \frac{\frac{V(x_0^{V'} - x_1^V)}{Lx_1^L + Vx_1^V} - \frac{V(1 - x_0^{V'} - 1 + x_1^V)}{L(1 - x_1^L) + V(1 - x_1^V)}}{\frac{V(x_0^V + x_1^V)}{Lx_1^L + Vx_1^V} - \frac{V(1 - x_0^V - 1 + x_1^V)}{L(1 - x_1^L) + V(1 - x_1^V)}}$$

$$\text{or: } E = \frac{x_0^{V'} - x_1^V}{x_0^V - x_1^V} = E_H$$

which is known as the Hausen efficiency [2] and represents in fig. 3 the fractional cut-off  $\frac{E''E}{BE}$

$$\text{or } \frac{F''F}{BF} \text{ or } \frac{B'C}{BC}$$

This definition of efficiency is the best one available in terms of a mathematical and physical

description of a contacting stage.

If  $L/V$  does not remain constant during the process of exchange the original equation (4) has to be inserted for both the theoretical as well as the actual contacting stage; then, however, the expression will be very complicated and does not reduce to simpler terms.

Standart [3] has tried to use a simplified equation for this situation, but although his definition of the efficiency comes down to an equal value irrespective whether it is related to gas phase parameters or to liquid phase parameters, the physical meaning of the numerical values which he obtained cannot be directly related to a degree of purification. Nevertheless in the limiting case, if  $L/V$  remains constant, Standart's definition also reduces to the Hausen efficiency.

However, The Hausen efficiency is seldom used in the profession, partly due to historical reasons, partly because the line CB, although it describes in mathematical terms the mass balance of the contacting stage, does seldom represent compositions of the two phases which are in near physical contact at certain points in the system.

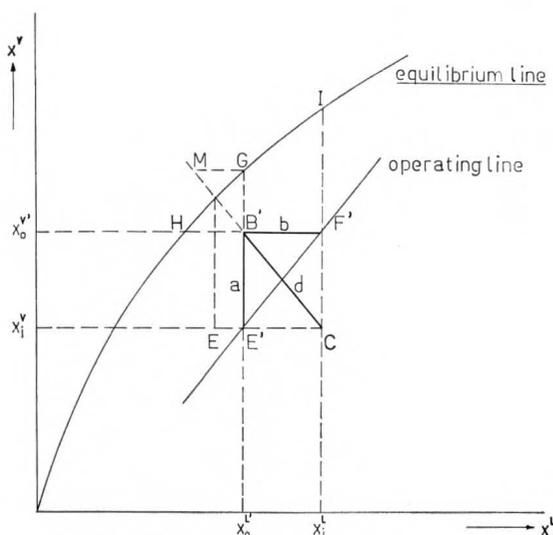
## REPRESENTING EXISTING CONCENTRATIONS

WE MAY TRY TO represent in the concentration diagram sets of concentrations in the two phases that are in close contact with each other. For actual stages often the two phases are contacted in cross flow, e.g. gas bubbling through holes in a plate while liquid traverses the plate from one side to the other.

If the liquid on the plate is well mixed, as will be the case for even relatively large plate diameters, then it has everywhere the composition  $x_0^L$  and line a (E'B') in Fig. 4 describes the concentrations in the gas phase which will occur along the height.

If the gas flows in plug fashion through the liquid all points of line a represent actual occurring pairs of concentrations; if the gas is mixed to some extent, the line will not start at point E' but somewhat higher. In the case that the gas also would be completely mixed, point B' would represent the concentration pairs on all points of the plate.

In the same way it can be shown, that line b (F'B') represents processes in which the gas phase is well mixed and the liquid phase flows in more or less plug fashion through the stage. This may be true in a shallow spray-tower. Here line b shrinks in the direction of B' when also mixing



**FIGURE 4. Composition diagram. Possible process paths.**

of the liquid phase occurs.

Line c, (CB') represents actual concentration sets if cocurrent flow exists without any extent of mixing in gas or liquid phase. All other types of contacting must be represented by other curved trajectories in the concentrations diagram. For all these systems except the case where the liquid is well mixed, the concentrations of the gas leaving the plate will differ for each local point.

If we assume that the liquid on a plate is well mixed vertically, although not necessarily so in the horizontal direction, then for each local point on the plate we may define a driving force for mass transfer between vapor and liquid. When the vapor below the plate is well mixed, its composition upon entering will be everywhere  $x_1^v$ . Then, depending upon the local point considered on the plate, the driving force for mass transfer will be in Fig. 4 the vertical distance from a point on line CE' to IG. If the vapour comes into equilibrium with the liquid, the driving force of the vapour upon leaving the plate will be zero. In practical circumstances this will not happen. Therefore the degree into which the driving force is reduced locally during passage through the liquid layer is called the point efficiency,  $E_p$ . The point efficiency is very difficult to measure, since both local concentrations of the leaving gas and liquid must be known. Moreover, as will be shown, the term efficiency is not appropriate.

If the liquid on the plate is well mixed horizontally too, then the point efficiency will be the same anywhere on the plate, and consequently the vapour leaving the plate will have the same

composition everywhere. This means that in this case the point efficiency is given by  $\frac{B'E'}{GE'}$ . Since this ratio for any practical stage is called the Murphree vapour efficiency,  $E_{MV}$ , this means that for plates with well mixed vapour entering and with perfectly mixed liquid on the plate, there is an equality between the point efficiency and the Murphree vapour efficiency. Now it can be seen that the Murphree efficiency is in fact not an efficiency, since a Murphree efficiency of 100% defined in the same terms, thus with point E' on the same point in the diagram, would correspond with point M for the mass balance, which is contradictory to the definition of a contacting stage. Of course, if the Murphree efficiency would rise, point E' also would shift to the left, until ultimately point E would be reached. This implies that the Murphree efficiency must not be considered as an efficiency in the pure meaning of the word, but as a qualitative measure for the contacting process that can be sensible in some circumstances viz. in those circumstances where on basis of a physical model the Murphree efficiency can be expected to remain constant with varying flow. In the same way a Murphree efficiency can be defined for the liquid phase:

$$E_{ML} = \frac{B'F'}{HF'}$$

It has equal drawbacks as those mentioned about for  $E_{MV}$ . Since the Murphree efficiency has shot so many roots in the field of distillation, it is not logical to eradicate its use. However, it should be realized that the Murphree efficiency does not provide a quantitative grip upon the number of steps which are actually needed in a distillation column. Then recourse has to be taken to the Hausen efficiency or what amounts to the same, to the equations describing mass balance and equilibrium themselves.

#### CASES WITH CONSTANTS

ALTHOUGH IT HAS BEEN shown in the foregoing, that a given Murphree plate efficiency cannot be translated directly into a purification grade, there do exist cases where a constancy of one of the Murphree efficiencies may be predicted on physical grounds.

For example, consider a distillation process in which:

- the liquid on the plate is completely mixed, while
- the gas moves in plug flow through the liquid

- Suppose that the gas flow is constant, while the liquid flow rate is varied, but
- the liquid height on the plate remains the same.

Now the real local liquid flow velocity will be made up by phenomena: a) the velocity induced by the overall liquid flow on the plate, and b) the statistical flow variations (mixing) caused by the action of the gas bubbles. It will be clear, that in most cases phenomena b) will be the one largely responsible for local fluid movement.

Therefore we may suppose, that a variation of the liquid flow rate on the plate will not influence directly the number of gas bubbles nor its dimensions, if the physical properties of the liquid on the plate remain the same (surface tension, viscosity, density). The physical properties are kept constant if the composition of the liquid on the plate is kept equal for different liquid flow rates,  $L$ , by adjusting the liquid feed composition. (from  $x_i^{L1}$  to  $x_i^{L2}$ ).

In this case a gas bubble rising in the liquid will not observe any change in its surroundings and therefore will transfer the same amount of mass regardless of the magnitude of  $L$  and hence  $E_{MV}$  is predicted to be constant. From Fig. 5 it is obvious, however, that only  $E_{MV}$  will be constant,  $E_H$  and  $E_{ML}$  will change with  $L$ . Experimental confirmation is given elsewhere [4].

In the same way it can be shown, that if

- the gas "on the plate" is well mixed
- the liquid moves in plug flow through the gas
- the liquid flow rate is constant
- the length of the liquid trajectory is constant, that the Murphree liquid efficiency,  $E_{ML}$  will be constant for different vapour velocities, but not so  $E_{MV}$  or  $E_H$ .

This type of exchange will be expected in a shallow spray tower (Fig. 6) Cases in which  $E_H$  is constant are very difficult to be thought of. But,

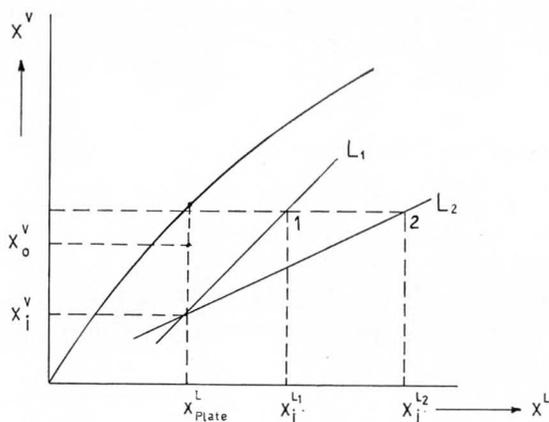


FIGURE 5. Constant  $E_{MV}$  as a function of  $L$ .  $x^L$  plate and  $V$  are constant.

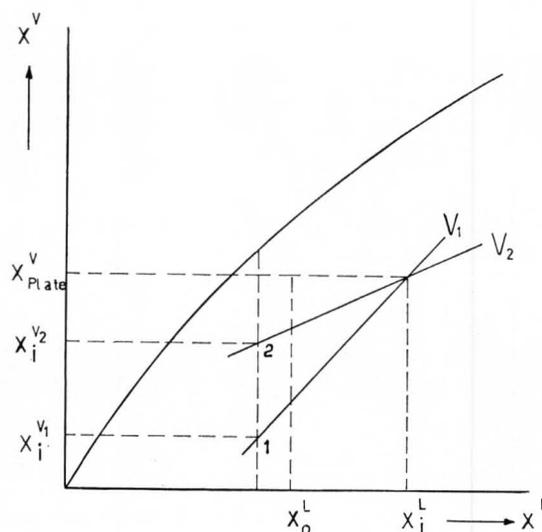


FIGURE 6. Constant  $E_{ML}$  as a function of  $V$ .  $x^v$  plate and  $L$  are constant.

then, the use of the Hausen efficiency, being consistent to a degree of purification, does not need further justification.

## CONCLUSIONS

There needs to be made a distinction between the degree of purification and the efficiency of a process. The degree of purification is derived on the basis of a mass balance, the efficiency must combine a mass balance with equilibrium relationship. The Hausen efficiency is based on a mass balance and an equilibrium relation and can readily be translated into a degree of purification. Numerical data on the Murphree vapour efficiency or the Murphree liquid efficiency, in general, do not provide complete quantitative information about the separation process. In certain circumstances the constancy of the Murphree vapour efficiency or the Murphree liquid efficiency may be expected on model considerations. □

## REFERENCES

1. van Ebbenhorst Tengbergen, H. J. and Rietema, K. in Rietema, K. and Verver, C. C., "Cyclones in Industry," Elsevier Publishing Cy, Amsterdam (1961).
2. Hausen, H. *Chemie Ing. Techn.* 25 (1953) 595.
3. Standart, G. *Chem. Eng. Sc.* 20 (1965) 611.
4. Moens, E. P. Drinkenburg, A. A. H. and van der Veen, A. J. *Trans. Inst. Chem. Engrs.* 52 (1974) 228.

## NOMENCLATURE

- $x$  : concentration, consistent with the unit of flow rate.  
 $L$  : flow rate phase 1  
 $V$  : flow rate phase 2 consistent with  $x$   
 $P$  : degree of purification  
 $E$  : efficiency  
 $E_H$  : Hausen efficiency  
 $E_{MV}$  : Murphree efficiency, based on the vapour  
 $E_{ML}$  : Murphree efficiency, based on the liquid.

## PROSPECTS OF POPULATION BALANCES: Ramkrishna

Continued from page 17.

ChE involve large populations, there are also situations in which small particle populations may be encountered. Thus bubble populations arising in a gas phase fluidized bed, continually agglomerate as they ascend through the bed, to form small populations. Such situations cannot always be described by population balance equations. Ramkrishna and Borwanker [23-25] have shown that the framework of population balances derives as a special case of the theory of point processes. Thus the population balance equation is shown to be the *first* of an infinite hierarchy of equations in what have been called as *product densities* all of which are required for the analysis of small populations in which random fluctuations may be important. Further, they have shown [25] that the model (5) normally used for agglomerating populations would be incorrect, when particle states are correlated. In such a case, additional members of the hierarchy of product density equations must be accounted for. Substantial particle size correlations have been predicted for some agglomeration probabilities. These have far-reaching practical implications. Thus in a fluidized bed reactor, one may raise the question as to whether or not randomly behaving bubble populations would give rise to fluctuations in reactor conversion.

Indeed, there are many engaging problems in the analysis of dispersed phase systems. Undoubtedly, considerably more detailed experimentation is required for further quantitative application of population balances. In view of the large variety of applications, the method of population balances deserves more vigorous pursuit. □

### REFERENCES

1. A. D. Randolph and M. A. Larson, "Theory of Particulate Processes", Academic Press, New York, 1971.
2. Bayens, C. A. and R. A. Laurence, *I.&E.C. Fundls.*, 1969, 8, 71.
3. Shah, B. H. and D. Ramkrishna, *Chem. Eng. Sci.*, 1973, 28, 389.
4. Hulburt, H. M. and S. L. Katz, *Chem. Eng. Sci.* 1964, 19, 555.
5. Eakman, J. M., A. G. Fredrickson and H. M. Tsuchiya, *Chem. Eng. Prog. Symp. Series*, No. 69, 1966, 62, 37.
6. Hulburt, H. M. and T. Akiyama, *I.&E.C. Fundls.*, 1969, 8, 319.
7. Argyriou, D. T., H. L. List and R. Shinnar, *A.I.Ch.E. J.*, 1971, 17, 122.
8. Ramkrishna, D., *Chem. Eng. Sci.*, 1971, 26, 1134.

9. Subramanian, G. and D. Ramkrishna, *Math. Biosci.*, 1971, 10, 1.
10. Ramkrishna, D., *Chem. Eng. Sci.*, 1973, 28, 1362.
11. Singh, P. N. and D. Ramkrishna, *Computers and Chem. Eng.*, 1977, 1, 23.
12. Singh, P. N. and D. Ramkrishna, *J. Colloid Interface Sci.*, 1975, 53, 214.
13. Spielman, L. A. and O. Levenspiel, *Chem. Eng. Sci.*, 1965, 20, 247.
14. Rao, D. P. and I. J. Dunn, *Chem. Eng. Sci.*, 1970, 25, 1275.
15. Collins, S. B. and J. G. Knudsen, *A.I.Ch.E.J.*, 1970, 16, 1072.
16. Zeitlin, M. A. and L. L. Tavlarides, *Can. J. Chem. Eng.*, 1972, 50, 207.
17. Shah, B. H., J. D. Borwanker and D. Ramkrishna, *Math. Biosci.*, 1976, 31, 1.
18. Ramkrishna, D., *Chem. Eng. Sci.*, 1974, 29, 987.
19. Madden, A. J. and B. J. McCoy, *Chem. Eng. Sci.*, 1969, 24, 416.
20. Narsimhan, G. and D. Ramkrishna, *Unpublished results*.
21. Curl, R. L., *A.I.Ch.E.J.*, 1963, 9, 175.
22. Bajpai, R. K., D. Ramkrishna and A. Prokop, *Chem. Eng. Sci.*, 1976, 31, 913.
23. Ramkrishna, D. and J. D. Borwanker, *Chem. Eng. Sci.*, 1973, 28, 1423.
24. Ramkrishna, D. and J. D. Borwanker, *Chem. Eng. Sci.*, 1974, 29, 1711.
25. Ramkrishna, D., B. H. Shah and J. D. Borwanker, *Chem. Eng. Sci.*, 1976, 31, 435.

### ACADEMIC POSITIONS

For advertising rates contact Ms. Carole Yocum, CEE c/o Chemical Engineering Dept., University of Florida, Gainesville, FL 32611

Applications are invited for appointment as Assistant Professor in Chemical Engineering. (Associate rank may be considered for an outstanding candidate). Qualifications required are a Ph.D. (or equivalent) in Chemical Engineering with research or industrial experience in fluidized reactor engineering. The successful applicant will be required to teach graduate and undergraduate courses in chemical engineering, including undergraduate core courses; and to conduct research and supervise graduate students in fluidized reactor engineering. The appointment is effective July 1, 1978. Closing date for applications is April 15, 1978. Applications including curriculum vitae and names of three referees may be sent to:

G. F. Chess, P. Eng.  
Acting Dean  
Faculty of Engineering Science  
The University of Western Ontario  
London, Ontario, Canada.  
N6A 5B9

# WHAT DOES THE PRACTICING ChE WANT IN MATERIALS EDUCATION?

RICHARD G. GRISKEY  
*University of Wisconsin-Milwaukee*  
*Milwaukee, Wisconsin 53201*

ONE OF THE QUESTIONS that continually perplexes ChE departments (as indeed all academic units) is how relevant are their course offerings. The Materials Engineering Science Division of A.I.Ch.E. recently undertook a survey that questioned their membership with respect to materials courses offered in ChE departments. The questionnaire (which also covered aspects of continuing education) is shown in Table 1.

Responses were obtained mainly from ChE's employed in industry (75% of all responses) and included Du Pont, Amoco, Monsanto, Dow, Shell, Owens-Corning, Allied, Continental Can, Dow Corning, Ray-O-Vac, Pitney-Bowes, Baxter Laboratories, Union Carbide and Hooker.

The interests (question 2) of the respondents was most heavily directed toward polymers (55%) and then toward metals (30%) and ceramics (14%). Some scattered interest was also indicated for inks, finishes, elastomers, composites, wood and cement.

## UNIVERSITY COURSE COMMENTS

THE RESPONDENTS developed the following ranking as to what the most important materials courses in the undergraduate ChE course should be:

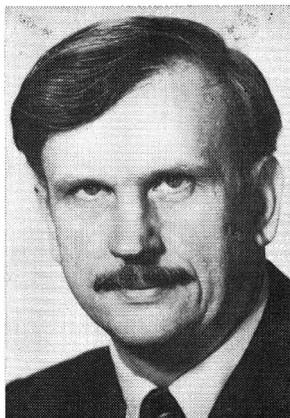
- Basic Materials Science (1.93)
- Materials Science (2.74)
- Polymer Engineering (3.80)
- Polymer Science (4.15)
- Physical Metallurgy (4.60)
- Process Metallurgy (5.20)
- Ceramics Engineering (6.20)
- Ceramics Science (6.25)

Figures in the parenthesis indicate the average of rank values given by respondents for each

TABLE 1  
MESD Education Questionnaire

1. Area where employed a) Industry b) Government  
(circle one) c) Higher Education
2. Materials areas of interest a) Metals b) Polymers  
c) Ceramics d) Other
3. What materials courses are most important in the undergraduate chemical engineering curriculum? (rank 1 to 8 with 1 most important)
  - a) Basic Materials Science
  - b) Materials Science
  - c) Process Metallurgy
  - d) Physical Metallurgy
  - e) Polymer Science
  - f) Polymer Engineering
  - g) Ceramics Science
  - h) Ceramics Engineering
4. What other undergraduate level materials courses would be most appropriate for chemical engineers.
5. What graduate level materials courses would be most appropriate for chemical engineers?
6. What short course continuing education materials courses would you like to see offered?
7. Please nominate potential instructors for these courses.
8. Would you like to have a materials oriented presentation(s) for your local section?    yes    no
9. If yes, what topics would appeal to you?
10. Please feel free to offer other comments, suggestions, etc. relating to Materials Education (use additional sheets if needed).

category. Additionally, there were a number of other types of undergraduate materials courses (question 4 of Table 1) that were indicated as being most appropriate for ChE students. These included relation of materials and design, plastics and elastomers, corrosion, joining of dissimilar materials, fiber science, composites, materials selection, production processes, electrochemistry, worldwide materials resources, fracture analysis,



**Richard G. Griskey** received his B.S. in Chemical Engineering from Carnegie-Mellon University in 1951. From 1951 to 1953 he was a First Lieutenant in the Combat Engineers of the U. S. Army Corps of Engineers. In 1953 he entered Carnegie-Mellon where he was awarded an M.S. (1955) and Ph.D. (1958).

The National Academy of Science appointed him as Senior Visiting Scientist to Poland in 1971. In the same year he was appointed Dean of the College of Engineering and Applied Science of the University of Wisconsin-Milwaukee as well as Professor of Energetics.

He has had industrial and consulting experience with DuPont, Celanese Fibers, Celanese Research, Phillips Petroleum, Thermo Tech Inc., Hewlett-Packard, Litton Industries and the U. S. Veterans Administration. He is a member of AIChE, Cryogenic Society, Society of Plastics Engineers, ASEE, and the Society of Rheology.

materials testing, environmental and stress behavior, economics of materials, surface chemistry and inter-relationship of energy, materials and ecology. The most frequently reported of these listed courses included corrosion, composites and materials selection.

Appropriate graduate level courses that were cited included composites, thermosets, mechanical behavior, (vibration, fatigue, fracture, etc.), corrosion, materials selection and design, adhesion, fiber science, plastics processing, ceramics, cellular materials, materials economics, polymer alloying and basic metallurgy. The most frequently named were composites, corrosion, plastics processing, ceramics, mechanical behavior and material selection.

From both the undergraduate and graduate course suggestions it becomes apparent that a real need is felt for formal course work on corrosion, composites, plastics processing and materials selection.

Recommended continuing education short courses (question 6) included thermosets, corrosion, materials selection, instrumentation materials for chemical processes, high temperature materials, advances in engineering materials, ma-

terials economics, electrochemical techniques, plastics process engineering, fracture analysis, coatings, polymer alloying and compounding and polymer engineering.

In a similar vein suggested presented for local sections included applications of new materials, plastics for corrosion and erosion service, composites, chlorine stress corrosion, polymer engineering, epoxy resins for environmental protective coatings, and materials economics. Presentations named frequently included composites, corrosion, polymer engineering and materials economics.

Interestingly, some sixty per cent of the respondents favored a materials oriented presentation for their local section (twelve per cent negative with the rest undecided).

One of the most enlightening sections of the questionnaire was item 10 for comments, suggestions, etc. A few extracted comments are given below:

"There is very little that A.I.Ch.E. seems to do for the engineer that works for a small company."

"Writing of specifications for materials purchases can be very critical. Help along this line could be helpful to all engineers."

"Students should have some laboratory corrosion testing experience."

"A systematic format for applying performance criteria to assist materials selection for non-structural process materials in critical usage needs to be developed."

"Wood should not be neglected as an engineering material."

"Materials courses appear to be too theoretical—more emphasis needed on applications."

## CONCLUSIONS

- Practicing chemical engineers whose primary activity is in the materials field regard Materials Science and Polymer Engineering as the most important materials courses for the undergraduate curriculum.
- Courses that respondents felt should be added to the undergraduate curriculum would deal with the areas of composites, corrosion and materials selection.
- Graduate courses in the areas of (2) as well as plastics processing were also felt to be needed.
- A majority of respondents desired some materials oriented presentations for their local section programs.
- Topics most frequently named to be of interest for local section presentation included composites, polymer engineering, corrosion and materials economics.
- A tabulation of potential continuing education short courses was developed from the study. □

## BOOK REVIEW: Statistical Methods

Continued from page 37.

follows the outline of this text is taught at Iowa State University for advanced undergraduate and graduate level engineers. This sequence has a laboratory associated with it in which the students can apply the statistical methods to problems in their particular area of engineering. For these problems, the students have access to a computer to perform most of the routine computations. This is particularly true for regression analysis and analysis of variance computations. This, I believe, is another shortcoming of this book; namely, very little mention is made of the availability of a computer to do much of the calculations. Most of the methods of regression analysis and analysis of variance are based on hand or desk calculator computations. These methods should be discussed with the use of a computer in mind.

Finally, as an introductory book for engineers, the important topics of (i) goodness of fit tests, (ii) propagation of errors and (iii) nonparametric methods are ignored or only treated briefly. The latter two topics are not covered while the chi-square goodness of fit test is used to test the parameter  $p$  of a binomial distribution and then it is mentioned that it can also be used for continuous distributions.

The authors do an excellent job of using examples to illustrate the statistical methods discussed. Most of the examples are related to chemical engineering. Also, each chapter contains many problems which should be interesting to the students (answers for selected problems are included).

In summary, the authors point out in the Introduction that "There are no statistical procedures which are applicable only to specific fields of study. Instead, there are general statistical procedures which are applicable to any branch of knowledge in which observations are made." This book introduces a subset of these procedures which are illustrated by examples taken from engineering. As such, there are several texts in this area which anyone considering a book for adoption might look at along with this book. □

### BLOCK AND GRAFT COPOLYMERIZATION, VOLUME 2

*Edited by R. J. Ceresa*  
*John Wiley and Sons, 1976.*

Reviewed by R. E. Cohen,  
Massachusetts Institute of Technology

The title of this book is misleading. Only about 75 of the more than 365 pages deal directly with

block and graft *copolymerization* (polymer synthesis). The remainder focuses on interesting and rather informative material regarding properties and engineering applications of certain block and graft copolymers. This particular volume (evidently the second of a series, although neither the contents of volume 1 nor of forthcoming volumes could be found) treats only two varieties of copolymers . . . Chapters 1 and 2 on Block Copolymer Polyol Surfactants . . . Chapters 3 and 4 on Block and Graft Copolymers of Poly (vinyl chloride).

The two chapters on polyol surfactants (by L.G. Lundsted and I.R. Schmolka) suffer from the shopping-list approach for presenting properties and potential applications. There is little attempt to provide any basic connection between copolymer synthesis, resulting molecular structure, and the properties observed. The excessive use of (bold face, capitalized) trade name acronyms tends to detract the reader. However, it should be noted that the authors and editor have organized the physical properties data into easily used tables and data-grids.

Chapter 3 on PVC blocks and grafts (by R. J. Ceresa) is without question the most satisfying in terms of technical content and adherence to the title of the book. In brief fashion (30 pages) the many possible synthesis techniques are reviewed and the resulting copolymer structures described. Chapter 4 (by D. Hardt) on properties and applications of PVC copolymers follows logically from the synthesis material presented earlier. There is better balance between structure-property relations and applications in this chapter than in the first two chapters of the book.

In addition to his work in Chapter 3, the editor is to be congratulated for a fine organizational job with the overall volume. Tables and figures are conveniently located in the text, the table of contents and appendices are very complete and detailed, and there is a novel "addendum" section put together just prior to publication in order to bring the reader up to date in a fast-moving area of polymer technology. In summary, this is a well organized book which should be of great value to readers with very *specific* interests in the two classes of polymers described; however, the level of general interest among polymer scientists and technologists will no doubt be minimal. □

of importance in petroleum refining has been an active area for Ron Danner and Tom Daubert. Three editions of the American Petroleum Institute's *Technical Data Book—Petroleum Refining* have been produced in the department since the project was originated by Merrill Fenske and Walter Braun in the early '60's. Further activity includes the very difficult problem of identifying readily measurable parameters for the characterization of petroleum fractions which are very complex and poorly defined mixtures. Ron and Tom have also been working on the development of generalized corresponding states methods for polar fluids and the measurement and correlation of gas mixture adsorption on solid surfaces.

#### • Dynamics

Bob Kabel, after developing a thorough understanding of the kinetics of certain acid ion exchange catalyzed reactions, has been using these reactions as a vehicle for understanding reactor dynamics. In particular, he has experimentally demonstrated the potential of forced periodic reactor operation to improve catalyst selectivity. Al Engel has experimentally demonstrated the use of forced cyclical operation of stirred tank reactors

to maintain transients in a neighborhood of an unstable steady state. Al's recent simulation work has shown that cyclical operation of a distillation column may produce energy savings approaching fifty percent of steady state operation for the same separation.

John Tarbell has been working on non-linear stability theory for reaction and reaction-diffusion processes. Liapunov's direct method provides the theoretical framework and irreversible thermodynamics provides an untapped source of Liapunov functions. Bifurcation phenomena, especially bifurcation to periodic and chaotic orbits are also being investigated.

In conclusion, we must emphasize that the success of our research programs has been and will continue to be a direct consequence of the dedication and perseverance of our graduate students. □

#### **BOOK REVIEW: Cellulose**

**Continued from page 23.**

posium participants were aware of the shortcomings of the enzyme studies. The results presented in these papers lack the *raison d'être* of the  $H_2O_2/Fe(II)$  studies, and it is not evident that they can be justified on the basis of Good Science. The chapter about lignin-degrading reactions is interesting, but very speculative. The conclusions that more data are needed and that they should relate to whole organisms rather than isolated organisms, are certainly valid. The summary statement about cellulase enzymes at the beginning of this section is well done, but it is sufficient.

"The Process" is the conversion of cellulose and lignocellulosic materials into glucose (or some other, equally useful product). The excellent chapter about physical and chemical features of cellulose and lignocellulosic materials would be better placed in the section about the substrate. This chapter is informative, and with its emphasis on susceptibility for the process, certainly not out of place where it is. The chapter that follows, also intended to be about the relationship between structure and process susceptibility, is a classic example of the ridiculous following the sublime. To be convinced of the former, one needs only to refer to the last figure and the claim that the different shapes of the curves drawn therein are significant. The chapter on pre-treatment and its

## **ChE** letters

### **SUMMER ENERGY-RELATED INSTITUTES**

Sir:

Oak Ridge Associated Universities will present four energy-related institutes for college faculty this summer. The institutes sponsored by the U. S. Department of Energy, DOE, are designed for faculty who teach or plan to teach energy-related courses. A limited number of stipends are available. The deadline for applying is March 31, 1978. The institutes to be presented are:

**ENERGY PRODUCTION AND THE ENVIRONMENT**

June 19-July 7, 1978

**ENERGY OPTIONS FOR THE FUTURE**

July 10-21, 1978

**ENERGY CONSERVATION:**

**THEORY AND PRACTICE**

July 10-28, 1978

**COAL PRODUCTION AND UTILIZATION**

July 31-August 11, 1978

Full information about the summer institutes and application material may be obtained from the Professional Training Programs, Manpower Education, Research and Training Division, Oak Ridge Associated Universities, P. O. Box 117, Oak Ridge, Tennessee 37830.

Roger J. Cloutier

discussion are not only excellent, but they also are concerned with an economically important aspect of the process. The chapter about enzymic saccharification of woody wastes is useful, but since it deals with only the *T. viride* cellulase, prospects for its ultimate commercial applicability are limited. Individuals with experience using enzyme kinetics will find the chapter about the kinetics of cellulose hydrolysis harmless, but others might not be so fortunate. Even if, as commonly happens in studies of homogeneous solutions of single enzymes, the assumptions (some unlisted, none justified) used to derive the well known equation for the reaction rate and its integral do not cause serious problems, the methods of data analysis (see Figures 2 and 3) used in this chapter probably will. The chapter about the economics of the enzymic conversion of cellulose to glucose is of pedagogical value. However, the very optimistic parameters used in the model (for example, raw material costs are estimated to be nil, and the recovery figure for active catalyst to be at least 3 times what one would expect on the basis of most experimental findings) not only strain the imagination, but probably invalidate even the order of magnitude of the cost estimate.

"The Product" is . . . ? The important point of the summary statement is that a diversity of products will strengthen the market for cellulose. The chapter about potentially useful products develops this idea in considerable detail. The products discussed include fuels, food and organic chemicals. There is also an interwoven discussion of product and process feasibility which includes the questionable suggestion that the old Fischer-Tropsch synthesis might be commercially useful now or in the near future. The excellent chapter on fuel gas production includes a survey of solid waste disposal technology followed by a description of a bioconversion process for the production of methane from waste cellulose. The discussion includes results obtained from a computer model and process optimization. These results indicate a 3-fold energy return in the form of  $\$2/10^6$  Btu methane in a  $\$22$  million plant capable of processing 1000 tons/day of solid waste. As in some of the previous cost estimates discussed at the symposium, these figures seem optimistic, in part because they do not include adequate research and development costs that would be necessary to iron the kinks out of a new process. The other chapters in this section are also highly recommended. The chapter about the acid-catalyzed

hydrolysis of waste illustrates that the conversion of pre-heated material to glucose can be modeled as an isothermal plug flow reactor with a residence time in the range of 20 to 30 seconds. This chapter, as well as the interesting ones by Miller and Finn discuss the bioconversion of cellulose-derived glucose into ethanol.

As mentioned above, two of the shortcomings of the cost estimates appearing in this volume are that they tend to be based on optimistic parameters, and that they seldom reflect sufficient R & D costs to achieve a smooth-running industrial process. Another shortcoming of these estimates is that they do not take into account the interactive economic forces that make these models so highly nonlinear. For example, ethylene and ethanol are interconvertible, but at present ethanol is made from ethylene because the cost of ethylene plus processing to ethanol is less than the price of ethanol available by other means. But what if ethanol could be made from cellulose at a price that was sufficiently below the current price of ethylene? The price of cellulose would probably increase, and that would cause the price of ethanol to go up. Furthermore, artificially-set oil prices would probably be decreased, and that would cause the price of ethylene to go down. Both factors would tend to favor the production of ethanol from ethylene even when conditions were reached which in present cost analyses would seem to favor the production of ethylene from ethanol. Thus, it would seem that the models used in some of the cost projections are incomplete.

But perhaps the models are nevertheless as good as they need to be. Although the editor is to be complimented for the speedy assimilation of the manuscripts, even a year renders many of the relevant cost analysis parameters hopelessly obsolete. One wonders, for example, if Miller's projected doubling of ethylene costs by 1975 occurred, and if so, what has happened to the cost of this important chemical now in 1978, three years later. Furthermore, there is considerable variation in the numerical values of parameters that don't depend on time. For example, if individuals at the same symposium disagree by 20% about the cellulose content of "most wood," refining the mathematical model might not improve the modeling result.

It seems to me that most of the cost predictions in this volume should be treated as a very rough, first approximation. Since large financial investments usually require more reliable forecasts, it is doubtful that much action will (or should) be taken on the basis of these analyses, at least in the near future. □

# Give Them A Strong Preparation

Tomorrow's chemical engineers must acquire a strong foundation of knowledge. These new Wiley texts help you give it to them...

## CHEMICAL ENGINEERING KINETICS AND REACTOR DESIGN

Charles G. Hill, Jr., University of Wisconsin

Here's a balanced discussion of chemical kinetics and chemical reactor design at an introductory level. In-depth coverage includes the analysis and interpretation of kinetic data, reaction mechanisms, adsorption phenomena and heterogeneous catalysis, and acid-base and enzyme catalysis reactions in liquid solution. The illustrative examples and problems throughout the text emphasize the analysis of representative data from the kinetics literature and the use of such data in preliminary reactor design calculations.

(0 471 39609-5) approx. 608 pp.  
1977 \$21.95 (tent.)

## ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES

Richard M. Felder, & Ronald W. Rousseau, both of North Carolina State University

A comprehensive and up-to-date introduction to chemical engineering principles and problem-solving techniques. Hundreds of examples and problems and several extended case studies of industrial processes illustrate the scope of activities encompassed by chemical engineering, both in the traditional areas of chemical processing and in such related fields as environmental science, energy conversion technology, and biomedicine.

(0 471 74330-5) approx. 576 pp.  
1978 \$19.95 (tent.)

## CHEMICAL AND ENGINEERING THERMODYNAMICS

Stanley I. Sandler, University of Delaware

This modern thermodynamics book — emphasizing a wide range of phase and chemical equilibria — is an ideal text for giving undergraduate students a thermodynamics background relevant to courses in mass transfer operations, plant design, and chemical reactor analysis. Students acquire an understanding of thermodynamics principles and their application to the solution of energy flow and equilibrium problems.

(0 471 01774-4) approx. 592 pp.  
1977 \$21.00

To be considered for complimentary examination copies, write to Art Beck, Dept. A8150-12. Please include course name, enrollment, and title of present text.

## DYNAMICS OF POLYMERIC LIQUIDS

Vol. 1: Fluid Mechanics, Byron R. Bird, University of Wisconsin, Robert C. Armstrong, Massachusetts Institute of Technology, & Ole Hassager, Institutet for Kemiteknik

Vol. 2: Kinetic Theory, Byron R. Bird, Ole Hassager, Robert C. Armstrong, & Charles F. Curtiss, University of Wisconsin

Vol. 1 describes the experimental and theoretical fluid mechanical methods of characterizing and predicting polymer flow behavior on the basis of measurable material properties. Its extensive coverage and range of viewpoints make it unique in its field.

Volume 2 presents kinetic theory methods for explaining and predicting the fluid mechanical behavior of polymers on the basis of molecular models. It includes an elementary introduction to the kinetic theory of macromolecular solutions, a thorough discussion of the classical Rouse-Zimm molecular theories of dilute macromolecular solutions, and a short treatment of the molecular network theory of polymer melts.

Vol. 1: (0 471 07375-X) 576 pp.  
1977 \$29.95

Vol. 2: (0 471 01596-2) 304 pp.  
1977 \$26.95

## FUNDAMENTALS OF MOMENTUM, HEAT, AND MASS TRANSFER, 2nd Ed.

James R. Welty, Charles E. Wicks, & Robert E. Wilson, all of Oregon State University

Revises and updates with current technology the unified treatment of transport processes. More details have been added, and areas where students have shown weakness have been strengthened by further discussion. New to this edition is the incorporation of SI units in a balanced treatment that includes English units as well. "Applications" chapters provide a basic knowledge of equipment. The text is ideal for junior-level engineering students with backgrounds in mechanics, mathematics, and introductory chemistry and physics.

(0 471 93354-6) 789 pp.  
1976 \$23.95

JOHN WILEY & SONS, Inc.  
605 Third Avenue New York, N.Y. 10016  
In Canada: 22 Worcester Road, Rexdale, Ontario  
Prices subject to change without notice. A8150-12





# GET INTO TOMORROW'S ENERGY.

## COULD THERE BE A MORE EXCITING FUTURE FOR TODAY'S SCIENTIFIC AND ENGINEERING GRADUATES?

Precious crude oil and natural gas are down under that water. And we're looking for people who know how to find it and what to do with it. Looking for new ways to put it to work for an energy-hungry America.

We're Chevron U.S.A. Inc. here in the United States, Standard Oil Company of California worldwide. One of the leaders in the petroleum industry. And Chevron Companies are into a lot more than off-shore drilling. We're into earth sciences. Petrochemicals. Hydroprocessing. Solar and geothermal energy. In fact,

virtually every area of energy production from The Netherlands to Australia. Our research programs read like science fiction.

Energy conservation? Environmental protection? 21st Century thinking? We're doing it all. And we have all kinds of opportunities for the graduate who wants to explore new frontiers. Write to Coordinator, Professional Employment, Standard Oil Company of California, 225 Bush St., San Francisco, California 94104. And be sure to say hello to our recruiter when he visits your campus.



**Standard Oil Company  
of California**

and

**Chevron Family of Companies**

An equal opportunity/affirmative action employer