



Berkeley's
JOHN PRAUSNITZ
and his

1975 Award Lecture
MOLECULAR THERMO
FOR CHEMICAL
PROCESS DESIGN

ChE at WORCESTER
POLYTECHNIC INSTITUTE

Saponification Experiment

S. W. WELLER

Process Control by the PSI Method

D. W. HUBBARD

FLOWTRAN Simulation in Education

J. P. CLARK AND J. T. SOMMERFELD

Mass Transfer Coefficients: An Analysis

J. D. MILLER AND T. R. REHM

An Ivory Tower Man Dines in the Real World

R. J. ROBERTUS

Can An Engineer Be Actualized?

J. C. BIERY



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CHEMICAL ENGINEERING DIVISION ACTIVITIES

3M Company Increases Annual Lectureship Award Grant

The 3M Company has increased their grant to cover the Annual Lectureship Award from \$2,500 to \$3,500. The change is effective for 1976 and the additional funds will be used to provide a \$500 honorarium to the awardee in recognition of the tour that he now makes to three schools where he presents the same lecture he gives at the Annual Conference.

The purpose of this award is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering

theory or practice. Bestowed annually on a distinguished engineering educator who delivers the Annual Lecture of the Chemical Engineering Division, the award consists of \$1,000 and an engraved certificate.

The 1975 ASEE Chemical Engineering Division Lecturer was Dr. John M. Prausnitz of the University of California, Berkeley. Dr. Prausnitz's lecture was entitled "Molecular Thermodynamics for Chemical Process Design."

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|------------|---|--|
| Event 1620 | STOP THE ROLLER COASTER WE WANT TO GET OFF — OR DO WE?
W. D. Baasal Session Chairman, Monday, 3:45-5:30 p.m. | L. C. Eagleton Session Moderator, Wednesday, 8:00-9:45 a.m. |
| Event 2135 | ChE Division Meeting
Business Discussions/Executive Session, Tuesday, 7:30 a.m. | Event 3415 ChE Division Luncheon, Wednesday, 12:00 Noon |
| Event 2520 | 3M AWARD LECTURE,
Tuesday, 1:45-3:30 p.m. | Event 2603 PREPARING ENGINEERS FOR THE FOOD INDUSTRY, Tuesday, 3:45-5:30 p.m. |
| Event 2735 | ChE Division Banquet
Sheraton Executive Park, Tuesday, 6:30 p.m. | Event 3310 LET'S NOT BOTCH METRIC CONVERSION, Wednesday, 10:00-11:45 a.m. |
| Event 3215 | FACULTY WORKLOAD MEASUREMENT | Event 4205 FOOD / ENERGY / ENVIRONMENT SYSTEMS, Thursday, 8:00-9:45 a.m. |
| | | Event 4320 Mini-Plenary FOOD/ENERGY ENVIRONMENTAL INTERFACE, Thursday, 10:00-11:45 a.m. (co-sponsored by AIChE). |

CORRECTION

Editor's Note: Professor John Prausnitz of the University of California, Berkeley has pointed out an error in the article on Professor John O'Connell in the Winter 1976 issue. He was quoted as saying that a chair that O'Connell used at Berkeley "originally belonged to the late Professor Latimer, discoverer of the hydrogen bomb (sic) when he was dean of the college." What Professor Praus-

nitz did write was ". . . Professor Latimer, discoverer of the hydrogen bond." Since the various drafts of the paper have been destroyed, no one here knows how the incorrect attribution occurred. (The editor's alibi is that he was in Venezuela when the letter from Prausnitz arrived.) But we all deeply regret the error and apologize to Professor Prausnitz for any embarrassment it may have caused him.

John Prausnitz of Berkeley

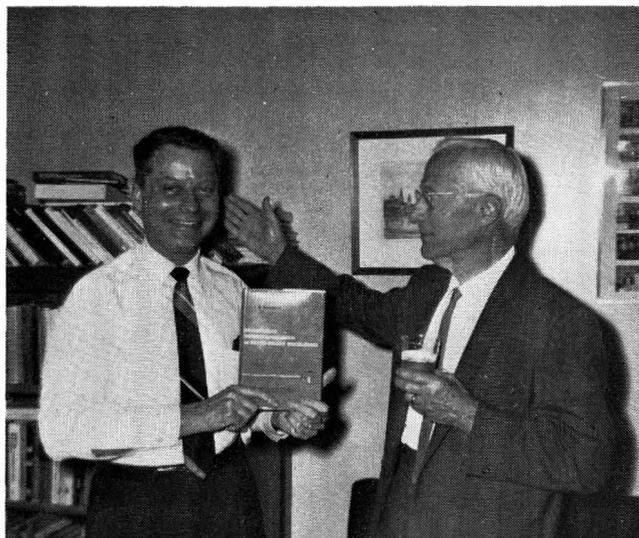
Prepared by a colleague,
C. J. KING,
*University of California
Berkeley, California 94720*

JOHAN PRAUSNITZ'S ASEE Chemical Engineering Division Award Lecture is published elsewhere in this issue. In it, John illustrates the utility of molecular thermodynamics for solving a number of key problems in the chemical processing industries. This is a concept which has guided his entire academic career. His goal has been to span the wide gap between the theories of physical chemistry, molecular physics and statistical mechanics, on the one hand, and the real needs of the design engineer, on the other.

How well John has succeeded in this mission is attested by the considerable impact his work

John has had a particularly close relationship, during his years at Berkeley, with Joel Hildebrand who at age 94 remains active in thermodynamics and interpretation of liquid-state properties.

has had on the petroleum and chemical industries. Most large companies in those fields have now based their phase-equilibrium prediction methods on his extensive publications and on approaches which he and his co-workers have developed. Two books by John and his colleagues—*Computer Calculations for Multicomponent Vapor-Liquid Equilibria* and *Computer Calculations for High-Pressure Vapor-Liquid Equilibria*, give predictive methods suitable for the computer.



John and Joel Hildebrand celebrate the publication of "Molecular Thermodynamics of Fluid Phase Equilibria".

They have been widely used and adapted in industry. John has himself been a regular consultant to a number of industrial companies, including Air Products and Chemicals Corp. (for 16 years), Union Carbide Corporation, and Fluor Corporation.

Table 1 shows the current affiliations of 40 Berkeley graduates who have received the Ph. D. during the period from 1959 to the present while carrying out research with John. The large number of petroleum, chemical and design and construction companies represented on the list is no accident, for many of these graduates are serving as principal sources of expertise on phase-equilibrium prediction and related problems. An estimate says that ten now have such roles, while most of the rest are carrying out functions that draw on their Prausnitz background in other ways. Some of those listed hold high managerial-level positions.

IMPACT ON EDUCATION

IT IS ALSO APPARENT from Table 1 that John has had great impact upon education, with graduates on the faculties of ten universities. Several of these professors have spread their activities into other areas, but all have an element to their work that clearly stems from Berkeley and molecular thermodynamics. Further, numerous visiting professors and post-doctoral fellows, many from Europe, have carried "the mes-

TABLE 1. Graduates Whose Ph.D. Theses were Supervised by John Prausnitz

UNIVERSITY FACULTY

Robert F. Blanks	Michigan State University
Alan L. Myers	University of Pennsylvania
Charles A. Eckert	University of Illinois
Henry M. Renon	Ecole des Mines, Paris
John P. O'Connell	University of Florida
H. Gordon Harris, Jr.	University of Wyoming
Clayton J. Radke	University of California, Berkeley
David C. Bonner	Texas A&M University
Juan H. Vera	McGill University, Montreal
Enrique R. Bazua	National University of Mexico

IN INDUSTRY

Elton J. Cairns	General Motors Corp.
Robert W. Hermsen	United Technology Corp.
Stephen A. Shain	Shell Development Co.
Newell K. Muirbrook	Exxon Research & Engineering Co.
Robert F. Weimer	Air Products & Chemicals Corp.
William J. Lawrence	United Technology Corp.
John F. Heil	Stauffer Chemical Corp.
Frank B. Sprow	Exxon Company, U.S.A.
Ping-Lin Chueh	Shell Development Corp.
Raymond N. Fleck	Union Oil Company
Constantine Tsonopoulos	Exxon Research & Engineering Co.
George T. Preston	Occidental Petroleum Corp.
Edward W. Funk	Exxon Research & Engineering Co.
Peter M. Cukor	Teknekron Corporation
Richard D. Newman	Gulf Oil Chemicals Co.
Cecil Chappelow III	Pfizer Corp.
Denis S. Abrams	Buffalo Salt Works, South Africa
Kwang W. Won	Fluor Corp.
Dennis P. Maloney	Exxon Research & Engineering Co.
Samil Beret	Union Carbide Corporation

IN GOVERNMENT

R. Norris Keeler	Chief Scientist, U.S. Navy
Albert E. Sherwood	Lawrence Livermore Laboratory
Sadok E. Hoory	Israel Atomic Energy Commission
William R. Parrish	National Bureau of Standards

OTHER

Ralph Anderson	Construction Business
Morton Orentlicher	Biomedical Research, Columbia Medical School
Robert V. Orye	Dental School
Gerrit J. F. Breedveld	Research Associate, UCB
Bryan L. Rogers	Sculptor
Kevin K. Tremper	Medical School

sage" back to their home institutions. *Molecular Thermodynamics of Fluid-phase Equilibria*, the Prausnitz text on molecular thermodynamics and ways of utilizing it, is found in classes at many universities both in the U.S. and abroad.

Many of John's publications are based on research done as independent projects by graduate students whose Ph. D. theses were directed by other faculty members. One example is the well-known gas-solubility correlation, co-authored by Fred Shair, now professor at Cal Tech; another one is the UNIFAC activity coefficient correlation co-authored by Professor Aa. Fredenslund (Denmark) and Russell Jones, now with Union Carbide.

... John is probably the one engineering professor anywhere to have produced a Ph.D. graduate (Bryan Rogers) with a joint degree in Chemical Engineering and Art, with ChE principles actually having been used as the basis for fluid kinetic sculptures.

John grew up in Forest Hills, N. Y., at that time a still-green, crime-free and pleasant part of New York City with open fields and wooded areas between ever-increasing urbanization. He attended Cornell as an undergraduate, in the Dusty Rhodes heyday. From this experience, he emerged a "pro" at technical writing, with a talent for clarity and standards still forcefully transmitted to students, and to faculty colleagues as well! He uses a red pencil for "ordinary" errors and a green one for those that are particularly offensive to his aesthetic sensibilities. He has a passion for hyphenating compound adjectives and has a running battle with copy editors who keep trying to take the hyphen out. With Robert Reid and the late Tom Sherwood, John recently completed the third edition of "Properties of Gases and Liquids," now in press. Will any hyphens remain in the final text?

After a year for a Master's at Rochester, John entered the Ph. D. program at Princeton. Although he already was intrigued by physical chemistry and by the broad power, universality and intellectual beauty of thermodynamics, he chose to work in the field of chemical reactor design for his Ph. D. research, so as to broaden his outlook and to enable a close association with Richard Wilhelm. John credits Wilhelm as one of the two great technical motivating forces in

One of his goals has been to span the wide gap between the theories of physical chemistry and molecular physics and statistical mechanics on the one hand, and the real needs of the design engineer on the other.

his career; the other one is Joel Hildebrand. After two years as Instructor at Princeton, John came to Berkeley as Assistant Professor in 1955, and has been there ever since.

Married in 1956, Susie and John live in the Berkeley Hills with their children, Stephanie and Mark.

During his reactor-design days at Princeton, John's interest in thermodynamics was rekindled by his almost accidental discovery of the books, "Solubility of Non-Electrolytes" by Hildebrand and Scott and "Mixtures" by Guggenheim. The fascination of those two books, so different in style and yet so similar in purpose, set the goal of his career—to apply physico-chemical principles for the development of efficient procedures for property estimation, vapor-liquid equilibria, solvent selection, etc., as needed for chemical engineering design. John has had a particularly close relationship during his years at Berkeley with Joel Hildebrand, who at age 94 remains active in thermodynamics and interpretation of liquid-state properties.

Responding to a challenge from Ted Szabo, a friend from Union Carbide and a connection made through former student Bob Blanks, John has devoted much of his recent efforts to the problem of understanding the complex phase behavior of polymer-solvent systems, especially at high pressures. This is a universal problem in polymer industries, and provides hopes for design modifications to minimize the considerable energy consumption of manufacturing processes for poly-

He chose to work in the field of chemical reactor design for his Ph.D. research, so as to broaden his outlook and to enable a close association with Richard Wilhelm. John credits Wilhelm as being one of the two great technical motivating forces in his career; the other one is Joel Hildebrand.

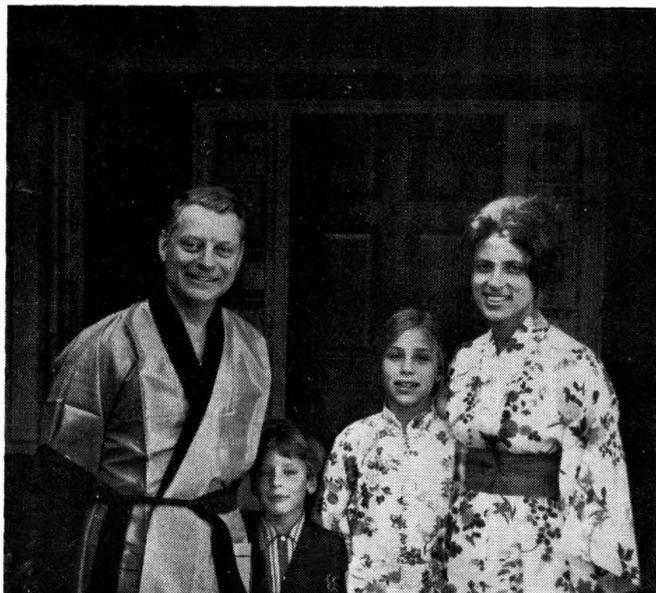
ethylene and other polymers.

John's many accomplishments were fittingly recognized by the Colburn and Walker Awards of AIChE and by election, in 1973, to the National Academy of Sciences.

Stemming from his German background, John is a sausage-loving Germanophile and Swissophile, having spent sabbatical leaves through Guggenheim Fellowships in Zürich (ETH) and Karlsruhe (Inst. für phys. chem.). He has this spring departed for another leave at the Technical University of Berlin, financed through the Alexander von Humboldt fellowship.

SATURDAYS WITH THE MET

HE IS A LOVER of classical music, stemming from WQXR in New York, and has maintained strong interests in the history of science (from



"Germanophile" Prausnitz occasionally travels westward as well. Here he is after returning from Japan, along with Susie, Stephanie and Mark.

Henry Guerlac at Cornell) and in philosophy and theology, stemming from encounters with Reinhold Niebuhr, Paul Tillich and Martin Buber at Princeton and in New York. Recently he served on the Ph. D. thesis committee of a student at the Berkeley Theological Union whose dissertation connected the thought of Jung, Kierkegaard and Niels Bohr. It is also no accident that John is probably the one engineering professor anywhere to have produced a Ph. D. graduate (Bryan Rogers) with a joint degree in Chemical Engineering and Art, with Chemical Engineering principles actually having been used as the basis

for fluid-kinetic sculptures.

On Saturdays, John is usually in his office, ostensibly to catch up on his voluminous correspondence. But intimates know the real reason is to hear the Metropolitan Opera broadcasts from New York.

Persistent rumors within the Department at Berkeley have it that John is a tennis player. Unfortunately his regular and obviously accomplished efforts on the courts seem to be carried out *sub rosa*, and the noontime Chem. E. faculty hackers league has yet to do him battle!

John is a lover of the outdoors, but only in moderation. His real preference is for Swiss-style hiking where, after a few miles in the woods, one can find a cozy restaurant. An annual event—most recently on the 100th anniversary of J. Willard Gibbs' great publication—is the grand trek and picnic of his research group and confrères to one of the more bucolic locations near the San Francisco Bay Area.

INSPIRATION AND CONSOLATION

THE JIMINY CRICKET of the Berkeley campus, John is one to keep colleagues, and particularly harassed Chairmen, well reminded of the

He is a lover of classical music, and has maintained strong interests in the history and in philosophy and theology, stemming from encounters with Reinhold Niebuhr, Paul Tillich and Martin Buber at Princeton and in New York.

more philosophical and idealistic sides of their university endeavors. With great skill, he manages to avoid administrative positions. However, he maintains a close watch on the progress of younger colleagues, offering an interested ear, discussions, probing questions and occasional hints on possible sources of research funds.

In his office he maintains a well-worn couch. It was intended to put students at ease but in fact it is used primarily by fellow faculty members who are in need of inspiration or, more often, consolation.

The Berkeley Chemical Engineering Department is only 30 years old. Much of what it has become is the result of the perceptive and able efforts and accomplishments of John Prausnitz. □

ChE news

PROFESSOR T. M. REED, UNIVERSITY OF FLORIDA

Dr. Thomas M. "Tim" Reed, III, Professor of Chemical Engineering, University of Florida, died of injuries from a car-bicycle accident, March 5, 1976. He was 54. He was co-author with K. E. Gubbins of the University of Florida of the book, "Applied Statistical Mechanics", McGraw-Hill, 1973 and papers in statistical mechanics and fluorocarbon chemistry. He received his Ph.D. from Pennsylvania State University and came to Florida in 1952. A memorial scholarship has been established in his name by the Chemical Engineering Department of the University of Florida. Contributions should be made payable to the University of Florida Foundation.

BARLAGE NAMED CLEMSON DEPARTMENT HEAD

William B. Barlage Jr., a native of Philadelphia, Pa., has been named head of the chemical engineering department at Clemson University.

Barlage, who began his Clemson teaching career in 1958, has directed six research projects totaling more than \$174,000 since 1961.

He is a former member of the advisory committee for chemical engineering technology at Greenville Technical College. In 1956 he was on the staff at North Carolina

State University, where he taught chemical engineering aspects of nuclear engineering to students visiting the United States under the Atoms for Peace program.

Barlage received the bachelor's degree from Lehigh University (1954), master's from the University of Virginia (1956), Ph.D. from North Carolina State University (1960), and completed post-doctoral study at the University of North Carolina at Chapel Hill (1962).

CALL FOR PAPERS FOR GRADUATE EDUCATION ISSUE

IN A LETTER DATED APRIL 19, 1976 EACH DEPARTMENT CHAIRMAN WAS ASKED TO SUGGEST FACULTY MEMBERS IN HIS DEPARTMENT WHO MIGHT BE INTERESTED IN PREPARING A PAPER FOR THE SPECIAL FALL 1976 ISSUE OF CEE GRADUATE EDUCATION ISSUE. THIS ISSUE CONSISTS MAINLY OF ARTICLES ON GRADUATE COURSES WRITTEN BY PROFESSORS AT VARIOUS UNIVERSITIES, AND OF ADVERTISEMENTS PLACED BY DEPARTMENTS OF CHEMICAL ENGINEERING DESCRIBING THEIR GRADUATE PROGRAMS.

IF YOU WOULD LIKE TO PREPARE A PAPER FOR THIS ISSUE PLEASE WRITE RAY FAHIEN, EDITOR, CEE C/O CHEMICAL ENGINEERING DEPARTMENT, UNIVERSITY OF FLORIDA, GAINESVILLE, FL 32611 OR CALL (904) 392-0861.

MOLECULAR THERMODYNAMICS FOR CHEMICAL PROCESS DESIGN

J. M. PRAUSNITZ
*University of California
Berkeley, California 94720*

THE IMPORTANCE OF thermodynamics in chemical engineering is so well established that today every undergraduate curriculum in chemical engineering includes at least one course in thermodynamics. Along with a few other subjects (e.g., transport phenomena, chemical kinetics, etc.), thermodynamics is recognized as one of the scientific cornerstones of chemical engineering science and practice.

Thermodynamics is a large subject with many possible applications; this article considers only that aspect of thermodynamics which is particularly important in chemical process design, viz., calculation of the equilibrium properties of fluid

Since the Scatchard-Hildebrand equation is not highly accurate, the design engineer faces the embarrassing problem of not knowing if the benzene comes out overhead or in the bottoms.

mixtures, especially as required in phase-separation operations. Design of most chemical processes requires at least some phase-equilibrium calculations since such processes, with rare exceptions, include separation steps effected by diffusional operations such as distillation, extraction, etc.

While the technical importance of thermodynamics is recognized by all chemical engineers, and while its intellectual eminence is duly recognized by chemical engineering professors, its practice by industrial design engineers, unfortunately, is often limited. This limitation is certainly not caused by any lack of books or articles since our library shelves groan with

publications on thermodynamics. Nor is this limitation caused by any lack of respect for or recognition of thermodynamics by practicing chemical engineers. Unfortunately, however, many practicing engineers feel a deep frustration when they try to *use* thermodynamics for practical purposes. The books are full of equations and more equations and still more equations, and while many data are reported in the literature, in a typical practical situation, they rarely pertain to the particular mixture of interest and even then only rarely to the particular desired conditions of temperature, pressure and composition. Therefore, many experienced chemical engineers are disillusioned by thermodynamics; they regard thermodynamics the way a movie buff looks at the latest x-rated movie: it promises so much more than it delivers.

Practical use of thermodynamics for phase equilibrium calculations is restrained by lack of appropriate data and by limited availability of methods for estimating needed mixture properties from a minimum of experimental information. Since the number of binary mixtures in current chemical technology is already extremely large, and since the possible number of multicomponent mixtures is larger than the United States national budget expressed in pennies, we may safely conclude that it is not possible that we shall ever have enough experimental data to satisfy all our needs. On the other hand, it is also unlikely that within the normal life span of even our youngest colleagues we shall be able to calculate thermodynamic properties of multicomponent liquid mixtures from a fundamental theory, that is, by solving the Schrödinger equation. Clearly, therefore, it is necessary that we interpolate and extrapolate limited experimental data to estimate the information needed for designing a particular process or a particular processing unit. To perform such interpolations and extrapolations, we require models and, to assure that these models

provide reliable answers, it is essential that they be based as much as possible on our growing knowledge of molecular behavior which, in turn, is expressed in macroscopic terms through statistical mechanics. When classical and statistical thermodynamics are combined with molecular physics, physical chemistry, limited experimental data and an efficient computer program, we obtain applied molecular thermodynamics. The purpose of this engineering tool is to provide the chemical engineer with the techniques that he needs to give him the equilibrium information required for process design.

To illustrate how molecular thermodynamics can help to solve engineering problems, four examples are briefly described in the following paragraphs. Each example refers to a real industrial situation.

RECOVERY OF BENZENE FROM A DILUTE SOLUTION OF SATURATED HYDROCARBONS

IN A REFINERY, a stream containing primarily C_6 saturated hydrocarbons also contains benzene in low concentration. This stream is blended with others for making gasoline but, considering the rising price of benzene, it appears to be economical to remove the benzene by distillation prior to blending. The obvious question facing the design engineer is: What is the volatility of benzene (B) at high dilution relative to hexane (H)? To obtain a reasonable first estimate we can calculate the activity coefficient of benzene using the Scatchard-Hildebrand equation as outlined in Figure 1.* When we do so, we find that

*All symbols are defined at the end of the article.

$$a_{B/H}^{\infty} = \frac{\gamma_{B/B}^{\infty} P_B^s}{\gamma_{H/H}^{\infty} P_H^s} \approx 1$$

B = Benzene
 H = Hexane
 P^s = Vapor Pressure
 γ = Activity Coefficient

"EXTENDED" SCATCHARD-HILDEBRAND THEORY

$$\ln \gamma_B^{\infty} = \frac{v_B}{RT} [(\delta_B - \delta_H)^2 + 2l \delta_B \delta_H]$$

$$\delta = \text{Solubility Parameter} = \left(\frac{\Delta E_{\text{vap}}}{v} \right)^{1/2}$$

$$\left(\frac{\Delta E_{\text{vap}}}{v} \right)_{BH} = \left[\left(\frac{\Delta E_{\text{vap}}}{v} \right)_B \left(\frac{\Delta E_{\text{vap}}}{v} \right)_H \right]^{1/2} (1-l)$$

In original (simple) theory $l = 0$

FIGURE 1. Relative Volatility of Benzene in Dilute Solution with Saturated Hexanes.

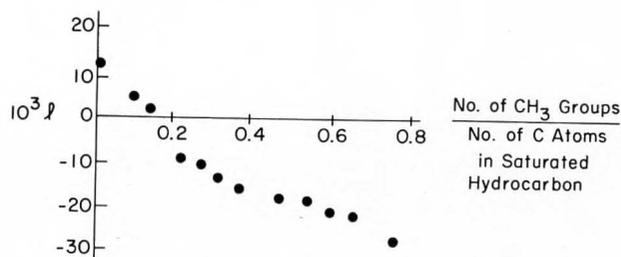


FIGURE 2. Correlation of Binary Parameter l with Methyl and Methylene Structure of Saturated Hydrocarbon.

$\alpha_{B/H}^{\infty}$ is uncomfortably close to unity. Since the Scatchard-Hildebrand equation is not highly accurate, the design engineer faces the embarrassing problem of not knowing if the benzene comes out overhead or in the bottoms.

The key simplification in the Scatchard-Hildebrand equation is the geometric-mean assumption which relates the cohesive energy density

$$\left(\frac{\Delta E_{\text{vap}}}{v} \right)_{BH}$$

to those of the pure components. This

assumption can be relaxed by introducing the binary constant l . Fortunately, experimental data for aromatic-saturated hydrocarbon systems are plentiful and therefore it was possible to establish a reasonable correlation for the binary parameter l as shown in Figure 2 taken from Funk [1]. The deviation from the geometric mean is related to the extent of branching of the saturated hydrocarbon; the branching parameter, shown on the abscissa, varies from zero (cyclohexane) to 0.8 (neopentane). Since the relative volatility depends not only on the solubility parameters, but also on l , to make rational design calculations, the design engineer must have some information on the extent of isomerization (branching) of the saturated-paraffin stream. With this information, parameter l can be estimated. Using Figure 2, it was possible to design the column with confidence and its performance corresponded fully to design specifications.

MODIFICATION IN THE AMMONIA-SYNTHESIS PROCESS

THE CONVENTIONAL HABER process for synthesizing ammonia from nitrogen and hydrogen must include a purge stream to remove unwanted methane and argon, as indicated in the top part of Figure 3. Small quantities of these inert materials unfortunately enter the reactor

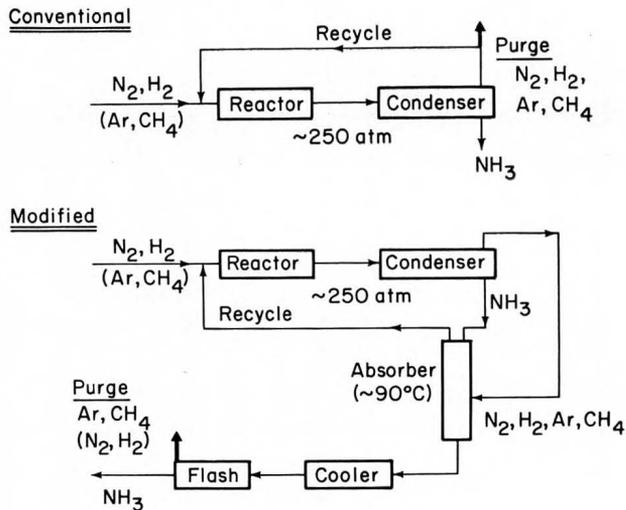


FIGURE 3. Modification of Ammonia Process: Reduction of Purge-Gas Losses.

and unless they are removed, they eventually accumulate to an intolerable level, making the process inoperable. The purge stream, while small, discards appreciable quantities of nitrogen and hydrogen and, what is economically most unattractive, it wastes the work of compression that has been expended to bring the thrown-away reactants to the high pressure at which the reactor must operate.

To minimize purge-stream losses, a modification of the ammonia process was suggested by Professor Scott Lynn [2], as shown in the lower part of Figure 3. In this modification the purge stream, at high pressure, is contacted with product liquid ammonia in an absorber, operating near 90°C. The absorber removes most of the unwanted argon and methane and allows most of the wanted nitrogen and hydrogen to be recycled to the reactor with essentially no work of compression. The effluent liquid ammonia, rich with argon and methane (and containing also some nitrogen and hydrogen), is then cooled and flashed. The advantage of this procedure is that the energy and material (H_2 , N_2) loss in the purge stream is minimized. (It may also be possible to recover the argon with subsequent processing, but this is a secondary refinement.)

The disadvantage lies in the capital investment needed to construct the high-pressure absorber. To investigate the economics of this process modification, it was necessary to estimate phase equilibria in the five-component system NH_3 - H_2 - N_2 - Ar - CH_4 at high pressure. An experimental study would require much time and expense and the usual thermodynamic methods

found in textbooks are of little use here because in this mixture we have one subcritical component and four supercritical components. To make reasonable estimates, Alesandrini [3] used some molecular-thermodynamic tools summarized in Figure 4. For the liquid phase he used a model of the van Laar type, suggested earlier by Chueh [4] and for the vapor phase, a modified Redlich-Kwong (RK) equation of state. This modified RK equation, in turn, was made possible by an earlier study of O'Connell [5] which had investigated the polar and nonpolar interactions of ammonia molecules. Since the pressure is high, the effect of pressure on the liquid phase (Poynting effect) had to be taken into account and this, in turn, was made possible by a correlation of liquid partial molar volumes published in 1965 by Lyckman and Eckert [6]. The large advantage of Alesandrini's thermodynamic method is that only pure-component and binary data are required to predict the five-component phase equilibria by solving the equations shown in Figure 5. A computer program, containing an efficient iteration scheme, was used to calculate the equilibria using the thermodynamic tools briefly mentioned above coupled with experimental Henry's constants for each of the four gases in liquid ammonia; fortunately these were available in the literature.

Some typical results from Alesandrini's calculation are shown in Figure 6. The gas composition (NH_3 -free basis) is shown at the top and, in this example, the pressure is constant at 200 atm. The right ordinate shows the overall solubility and the left ordinate shows the individual solubilities, both as a function of temperature. The mole fraction of ammonia in the gas phase is also shown. A few well-selected experimental

Fugacity Coefficient Φ

Modified Redlich-Kwong equation of state.
Modification based on analysis of potential energy function for ammonia (O'Connell).

Partial Molar Volume \bar{v}

Correlation based on cohesive energy density concept (Lyckman and Eckert)

Activity Coefficients γ_1 and γ_1^*

Modified Van Laar Model (Chueh)

Henry's Constant H

Reduction of binary NH_3 -solute data

FIGURE 4. Calculation of Thermodynamic Properties Needed for Solution of Phase-Equilibrium Equations.

$$\text{NH}_3 \text{ (I)} \quad \varphi_i y_i P = \gamma_i x_i f_{\text{pure } i}^L \exp \int_{P^S}^P \frac{\bar{v}_i dP}{RT}$$

(Subcritical)

$$\text{H}_2, \text{N}_2, \text{Ar}, \text{CH}_4 \text{ (i)} \quad \varphi_i y_i P = \gamma_i^* x_i H_{i,1} \exp \int_{P^S}^P \frac{\bar{v}_i dP}{RT}$$

(Supercritical)

P = Pressure φ = Fugacity Coefficient
 x = Mole fraction (liquid) \bar{v} = Partial Molar Volume
 y = Mole fraction (vapor) γ_i & γ_i^* = Activity Coefficient
 T = Temperature H = Henry's Constant
 R = Gas Constant

$$\gamma_i \rightarrow 1 \text{ as } x_i \rightarrow 1$$

$$\gamma_i^* \rightarrow 1 \text{ as } x_i \rightarrow 1 \left(\sum_{i \neq 1} x_i \rightarrow 0 \right)$$

FIGURE 5.
 CALCULATION OF VAPOR-LIQUID EQUILIBRIA FOR
 NH₃-H₂-N₂-Ar-CH₄

measurements by Alesandrini served to indicate that the calculated equilibria are sufficiently accurate for approximate design purposes. With these calculated phase equilibria it was then possible for Professor Lynn to make some economic evaluation of his modified ammonia process. While conclusions are not definite, it appears that under some circumstances the modified process may offer appreciable economic advantages. It would have been impossible to make even an approximate economic analysis without some reasonable estimates of the phase equilibria and these, in turn, could only be made because research had previously been performed on pertinent topics in molecular thermodynamics.

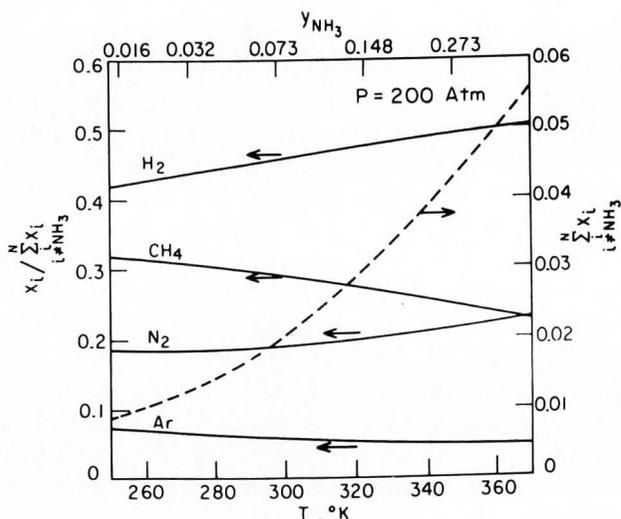
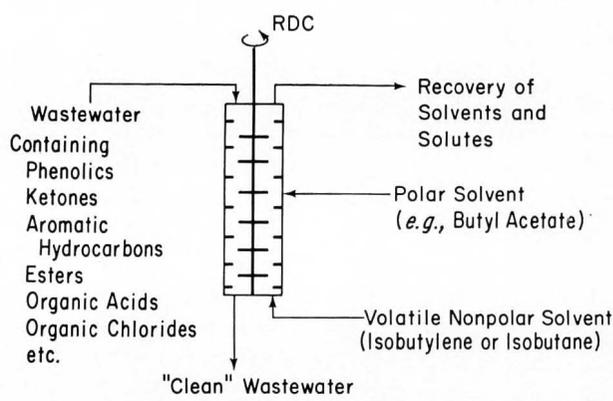


FIGURE 6.
 VAPOR-LIQUID EQUILIBRIA AT 200 ATM
 ($y_{\text{H}_2} : y_{\text{N}_2} : y_{\text{Ar}} : y_{\text{CH}_4} = 3.0 : 1.0 : 0.18 : 0.44$)

DEVELOPMENT OF A DUAL-SOLVENT EXTRACTION PROCESS FOR REMOVAL OF ORGANIC POLLUTANTS FROM INDUSTRIAL WASTEWATERS

WASTEWATERS IN PETROLEUM refineries and petrochemical plants frequently contain appreciable amounts (a few wt. per cent) of dissolved organic matter; much of this organic matter (especially phenolics) is offensive in odor and does damage to marine life. To avoid overloading of biological wastewater-treatment ponds, it is often desirable to remove 90 or 99% of the pollutants prior to biological treatment. The economics of such extraction may be particularly attractive if the recovered pollutants have commercial value.



Polar solvent extracts hard-to-get solutes (e.g., phenolics).
 Volatile nonpolar solvent extracts (slightly) water-soluble polar solvent.

FIGURE 7. Dual-Solvent Extraction Process for Wastewaters from Petrochemical Plants.

To remove phenolics (and other polar organic solutes) from water by extraction, it is necessary to use an organic solvent which is polar; hydrocarbon solvents, even aromatics, have low distribution coefficients for phenolics and similar pollutants. However, a typical polar organic solvent is somewhat soluble in water and therefore, while the polar solvent may efficiently remove the pollutants, it becomes a pollutant itself. Further, the density of a typical polar solvent is often uncomfortably close to that of water, thereby creating mechanical difficulties (flooding) in the extractor at economic flow rates. To circumvent these difficulties, it appeared desirable to consider a dual-solvent extraction process as shown in Figure 7. The primary solvent (e.g., butyl acetate) efficiently removes phenolics and many other organic solutes but, since the solubility of butyl acetate in water is not negligible, it is necessary to remove it with another solvent which in this

case is isobutane or isobutylene. A rotating disc column (RDC) is useful for this process. Wastewater enters at the top and the C₄ hydrocarbon enters at the bottom of the column. Near the middle of the column, butyl acetate is introduced. Since the density of C₄ is much lower than that of butyl acetate, the density of the organic phase is always well below that of water, allowing relatively large flow rates without flooding. The highly favorable distribution coefficients for the pollutants, distributing themselves between water and the mixed organic phase, permit operation at low solvent-to-water flow ratios. The high volatility of C₄ is also beneficial in subsequent processing steps to recover the solvents. The RDC operates at slightly elevated pressures, in the region 40-50 psia.

To design this extraction process and to evaluate its economic potential, it was necessary to obtain distribution-coefficient data. For a non-volatile solvent like butyl acetate such data are obtained easily. But for volatile solvents, distribution data must be obtained under pressure and the necessary experimental work is much more difficult. Nevertheless, an apparatus and procedure for obtaining such data was developed by K. W. Won, as described elsewhere [7]. To minimize the experimental effort, it was desirable to obtain only a few representative experimental results and then to generalize (correlate) these with the help of molecular thermodynamics.

A simple technique for achieving at least partial correlation is outlined in Figure 8. The distribution coefficient \bar{K} consists of two parts: first, the difference in work that must be done to create a hole in the solvent and to collapse a hole in the water as the solvent moves from one phase to the other and second, the difference in attractive energy experienced by the solute as it exchanges its aqueous environment to a hydro-

$$\ln K = \frac{kq}{RT} + \frac{\Delta U}{RT}$$

q = Size parameter for solute

$$kq = k'q - k''q$$

$k'q$ = Work needed to make "hole" for solute in water

$k''q$ = Work needed to make "hole" for solute in solvent

$$\Delta U = U' - U''$$

U' = Attractive energy for solute in water

U'' = Attractive energy for solute in solvent

FIGURE 8. Distribution Coefficient \bar{K} is Correlated by Perturbed-Hard-Sphere Theory of Solutions.

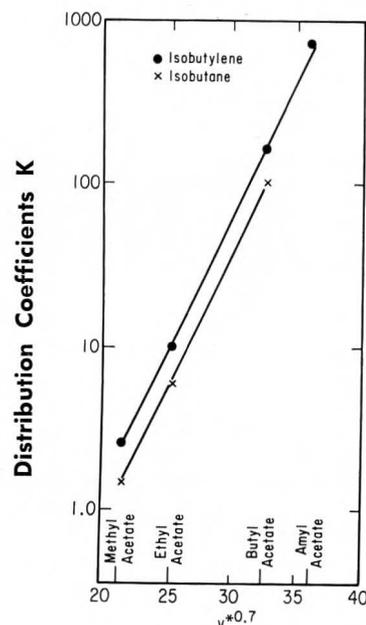


FIGURE 9. Distribution Coefficients \bar{K} at 25°C for Acetates. Units of V^* are cm^3/mol . (K = moles acetate per kilogram of hydrocarbon/moles acetate per kilogram of water).

carbon environment. The derivation of the equation shown in Figure 8 is given elsewhere [7]; it is based on a very simple theory of dilute solutions, which, in similar forms, has often been used in the physico-chemical literature, especially for pharmaceutical applications. For our purposes here, we only want to show how such a simple theory can be used to obtain straight-line correlations for different solute families as shown in Figures 9 and 10 where size parameter q has been replaced by $(V^*)^{0.7}$. The solute-size parameter V^* is obtained from fundamental pure-component thermodynamic data. The exponent 0.7 was chosen because it is not clear whether the work to create a hole is proportional to the size V^* or to the surface area which, at least for spheres, is given by $(V^*)^{2/3}$. Empirically it was found that 0.7 gives the best straight-line correlation for the solutes considered in this particular extraction process. Figures 8, 9 and 10 illustrate that simple molecular ideas can reduce experimental effort by providing a reasonable basis for interpolation and extrapolation of limited experimental data.

Bench-scale pilot plant studies by Earhart [8] have shown that the extraction process outlined in Figure 7 has considerable potential for economic wastewater treatment.

OPTIMIZATION OF THE SEPARATION STEP PRIOR TO RECYCLE OF ETHYLENE IN THE HIGH-PRESSURE PROCESS FOR POLYETHYLENE

IN 1974, ANNUAL production of polyethylene was slightly in excess of four million tons. Much of this polyethylene is made by the high pressure process, shown schematically in Figure 11. Per pass, the conversion of ethylene to polymer is in the region 10-30% and it is therefore necessary, at the reactor outlet, to separate unreacted ethylene from the product stream, prior to recompression and recycle. Separation is easily achieved by decompression since the solubility of ethylene is strongly pressure-dependent. The lower the pressure in the separator, the better the separation. But the lower the pressure

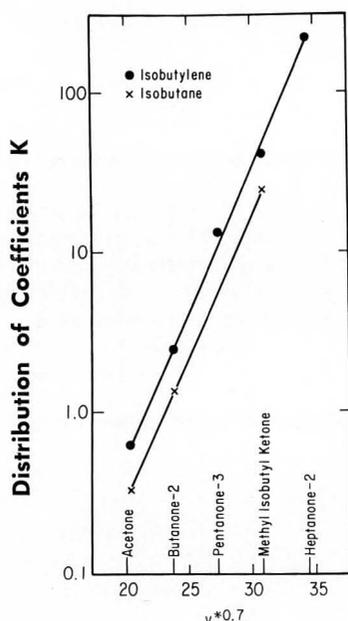


FIGURE 10. Distribution Coefficients K at 25°C for Ketones. Units of V^* are cm^3/mole . (K = moles ketone per kilogram of hydrocarbon/moles ketone per kilogram of water).

in the separator, the larger the cost of recompression of unreacted ethylene for recycle to the reactor. Since energy costs are significant in this process, it is important for optimum design to give careful attention to the pressure at which the separator should operate or, if a series of separators is used, what pressure should prevail in each individual separator. For design optimization therefore, it is necessary to have quantitative information on phase equilibria in the ethylene-polyethylene system.

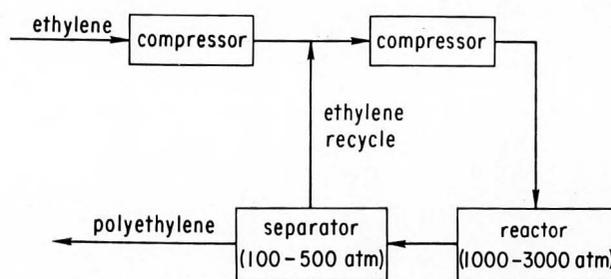


FIGURE 11. Schematic Flow Diagram of High-Pressure Process for Polyethylene.

If the polyethylene is monodisperse (all polymer molecules have the same molecular weight), the phase diagram has the general features shown in Figure 12. At very high pressures, ethylene and polyethylene are completely miscible but, as the pressure falls, separation occurs. At low pressures there is very limited solubility of ethylene in the polymer-rich phase and essentially no solubility of polymer in the ethylene-rich phase.

To obtain a quantitative estimate of the desired phase equilibria, it is necessary to use a molecular model, in this case, an equation of state suitable for polymer-monomer mixtures at intermediate and high pressures. The common equations of state (e.g., Redlich-Kwong, Benedict-Webb-Rubin, etc.) are not applicable here since these are intended for relatively small molecules, not polymers. However, Flory, Patterson and other physical chemists have proposed an equation of state based on Prigogine's theorem of corresponding states for chain molecules. This equation of state, shown in Figure 13, can be used with standard thermodynamics to calculate component fugacities and from these, quantitative phase relations can be obtained.

The fundamental idea of Prigogine is illustrat-

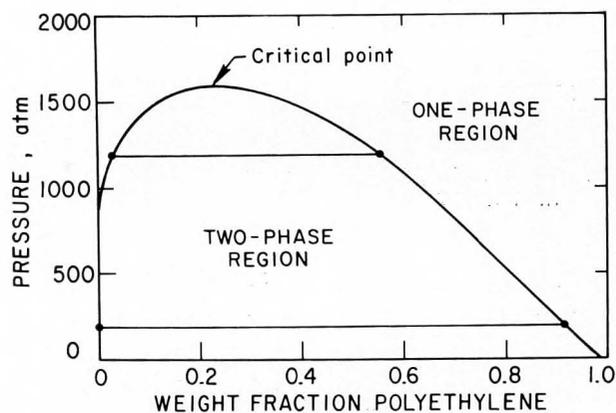


FIGURE 12. Ethylene-Polyethylene Binary Coexistence Curve (Constant T & Molecular Weight).

$$\frac{\tilde{P}\tilde{V}}{\tilde{T}} = \frac{\tilde{V}^{1/3}}{\tilde{V}^{1/3}-1} - \frac{1}{\tilde{V}\tilde{T}}$$

$$\tilde{V} = \frac{V}{V^*} \quad \tilde{P} = \frac{P}{P^*} \quad \tilde{T} = \frac{T}{T^*}$$

- v^* = Hard-core (van der Waals) volume per segment
 P^* = $s\eta/2v^{*2}$
 T^* = $s\eta/2ckv^*$ k = Boltzmann's Constant
 s = Number of external surface sites per segment
 η/v = Potential energy per surface-site contact
 $3c$ = Number of external degrees of freedom (translation, large-scale rotations and vibrations)

Parameters v^* , P^* , and T^* obtained from PVT data

FIGURE 13. Equation of State for Polyethylene, Ethylene, and Their Mixtures at High Pressures.

ed in Figure 14. In the upper part we show a container of volume V containing Nr monomer molecules at temperature T . In the lower part we show a container of the same volume V at the same temperature T , containing N polymer molecules where each polymer molecule consists of r units (or segments); the total number of segments, then, is Nr . In both containers, therefore, the density is the same, viz. Nr/V . But clearly there is a difference between the two situations. The difference is that in the upper diagram the total number of external degrees of freedom is $3Nr$ (each molecule has 3 translational degrees of freedom) while in the lower diagram, due to chemical bonding of the segments, the total number of external degrees of freedom is smaller. How much smaller? There are $3N$ translational degrees of freedom but there are also many degrees of freedom due to rotation and vibration of the segments. Some of these are external (i.e., they are affected by the presence or absence of neighboring molecules) while others are internal (i.e., they are independent of density). The total

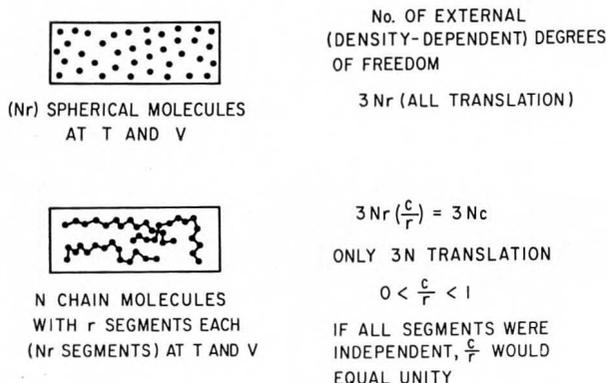


FIGURE 14. Corresponding States for Chain Molecules.

number of external degrees of freedom in the lower diagram is equal to $3Nr(c/r)$ and Prigogine's theorem of corresponding states assumes that all of these can be treated as if they were equivalent translational degrees of freedom. The parameter c/r lies between zero and unity. If the polymer molecule is stiff (uncooked spaghetti), $c/r \ll 1$ because in a stiff molecule rotations and vibrations are severely limited. On the other hand, if the polymer molecule is highly flexible (cooked spaghetti) c/r may be in the region 0.5-0.8; only in the limit, when all segments can act independently (all segment-segment bonds are broken) does c/r attain a value of unity.

The equation of state shown in Figure 13 contains three molecular reducing parameters, here called v^* , T^* and P^* ; the first of these reflects the hard-core size of the molecules (or segments) and the other two, in combination, reflect the characteristic segment-segment potential energy and the "flexibility" parameter c . Numerical

This article considers only that aspect of thermodynamics which is particularly important in chemical process design, viz., calculation of the equilibrium properties of fluid mixtures, especially as required in phase separation operations.

values of these parameters can be obtained from fitting the equation of state to experimental volumetric (PVT) data which are available for polyethylene and for dense ethylene. The equation of state can be applied to mixtures using reasonable mixing rules.

In a real industrial situation, the polymer in the product stream is not monodisperse, but polydisperse and, therefore, the mixture is not a binary but a multi-component mixture. A realistic distribution of molecular weights of polyethylene is shown in Figure 15; this particular distribution is a log-normal distribution whose number-average molecular weight is given by \bar{M}_N and whose first and second moments are those indicated.

Using the equation of state based on Prigogine's theorem, the molecular-weight distribution shown, and a suitable computer program, it is possible to calculate phase equilibria in the separator [9]. Some results are shown in Table 1; these were calculated at 260°C for an entering stream containing 12.5 wt % polymer. At the lowest pressure (200 atm), the separation is

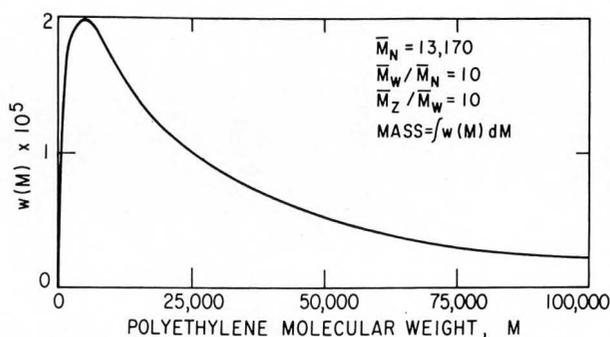


FIGURE 15. Log-Normal Molecular Weight Distribution.

sharp but at the highest (900 atm), the separation is poor: the heavy phase retains 21.8 wt. % ethylene and the light phase retains 7.5 wt. % polyethylene. Table 1 also gives the number-average molecular weights of both phases (ethylene-free basis) and finally, the molecular-weight distributions for both phases at 900 atm. are shown in Figure 16.

A variety of factors must be taken into account by the design engineer toward optimizing the high-pressure polyethylene process. Phase equilibria constitute only one of these factors but surely it is of utmost, indeed essential, importance. The type of phase equilibrium information required in this case is very difficult to obtain experimentally. However, as outlined above, an appropriate physicochemical model, coupled with a few well-selected experimental data, can provide the design engineer with estimates of the equilibria he needs for making rational decisions (10).

CONCLUSION

THE FOUR EXAMPLES briefly described here illustrate how molecular thermodynamics can be of direct use in practical chemical engineering. The essential ingredients are classical ther-

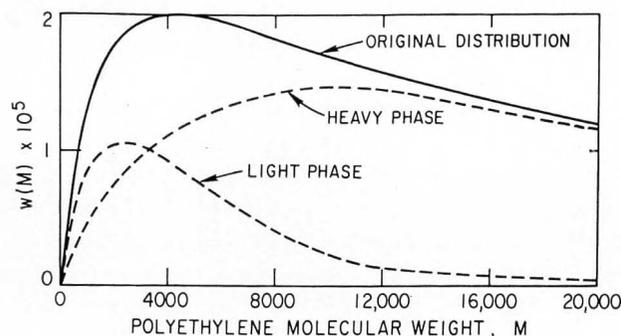


FIGURE 16. Molecular Weight Distributions in Equilibrium Phases (at 260°C & 900 Atm.).

modynamics, molecular physics or physical chemistry and an efficient computer program; in some cases, but not all, statistical thermodynamics is also required.

When we look at the recent work of chemical physicists and physical chemists, we find that every month new quantitative results are reported in a language with which most chemical engineers are not familiar; as is well known, each profession has its own jargon. The role of molecular thermodynamicists is to bridge the gulf between the needs of the process design engineer and the research achievements of those scientists who discover new facts about molecular behavior. This gulf, unfortunately, is increasing. On the one hand, the variety of tools needed by the design engineer is rapidly growing with the size and sophistication of expanding chemical industry,

TABLE 1
Effect of Separator Pressure on
Ethylene-Polyethylene Equilibria at 260°C
(Feed Stream Contains 12.5 wt. % Polymer)*

	200	500	900 atm.
Wt. % of total polyethylene retained in light phase	0.01	0.30	7.50
Wt. % of total ethylene retained in heavy phase	1.10	4.80	21.8
\bar{M}_N in light phase (ethylene-free basis)	110	440	2600
\bar{M}_N in heavy phase (ethylene-free basis)	13350	14350	19500

*Molecular wt. distribution of the polymer feed is shown in Figure 15.

and on the other, refinements of scientific concepts and experimental instruments makes it ever more difficult for nonspecialists to understand the significance and implications of new scientific insights and discoveries. Historically, it is clear, however, that progress in developing better design tools can come only from a better appreciation of new scientific results, tempered by mature judgment but also propelled by daring initiative. The innovative elements of creative chemical engineering are numerous but, for efficient design of chemical plants, it is evident that molecular thermodynamics is often required to reduce them to practice.

ACKNOWLEDGMENT

The author is grateful to the 3M Company which sponsors the ASEE Chemical Engineering Division Lectureship and, for support of research, to the National Science Found-

dation, the Environmental Protection Agency, the Donors of the Petroleum Research Fund administered by the American Chemical Society, Union Carbide Corporation and Gulf Oil Chemicals Company. □

NOTATION

- 3c = total number of external degrees of freedom per molecule
- ΔE_{vap} = energy of isothermal vaporization from the saturated liquid to the ideal gas
- f = fugacity
- H = Henry's constant for a gaseous solute in liquid ammonia
- k = a proportionality constant (Figure 8)
- k = Boltzmann's constant (Figure 13)
- \underline{K} = distribution coefficient for a solute between water and an organic liquid phase
- l = a binary parameter characterizing deviation from the geometric-mean assumption
- \overline{M}_N = number-average molecular weight
- N = number of polymer molecules
- Nr = number of polymer segments (or monomers)
- P = total pressure
- P^s = saturation (vapor) pressure
- P^* = a characteristic molecular parameter having units of pressure
- q = a molecular size parameter
- R = gas constant
- T = absolute temperature
- T^* = a characteristic molecular parameter having units of temperature
- U = attractive energy of one mole of solute molecules at very high dilution in a liquid solvent
- v = liquid molar volume (Figure 1)
- v = volume per segment (Figure 13)
- \bar{v} = partial molar liquid volume
- V = total volume (Figure 13)
- V^* = characteristic (hard-core) volume, per mole
- w(M) = frequency of molecular weight M in molecular-weight distribution
- v^* = characteristic (hard-core) volume per segment
- x = liquid-phase mole fraction
- y = vapor-phase mole fraction
- $\alpha_{B/H}^\infty$ = relative volatility of benzene infinitely dilute in hexane
- δ = solubility parameter
- ϕ = vapor-phase fugacity coefficient
- γ_1 = activity coefficient (normalized such that $\gamma_1 \rightarrow 1$ as $x_1 \rightarrow 1$)
- γ_i^* = activity coefficient (normalized such that $\gamma_i^* \rightarrow 1$ as $x_i \rightarrow 0$)

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The History of Quantum Theory, Friedrich Hand, translated by Gordon Reece. Published by Barnes and Noble, New York, 260 pages. This book provides a survey of the history of quantum theory for students and those who may not have much knowledge of quantum theory.

Elementary General Thermodynamics, M. V. Sussman. Published by Addison-Wesley Publishing Co., Reading, MA, 444 pages. This book presents a broad introduction to thermodynamic thought and methodology, and applications to many branches of engineering and science.

Process Engineering with Economic Objective, G. L. Wells. Published by Halsted Press, div. of John Wiley & Sons, New York, 168 pages. This guide to process engineering with economic objective serves as an introduction and to integrate the fuller instruction available from specialist texts.

Professional Obsolescence, edited by S. S. Dubin. Published by Lexington Books, div. of D. C. Heath & Co., Lexington, MA, 121 pages. This book is a record of a symposium on combatting professional obsolescence held at Churchill College, Cambridge (1970) under auspices of the Scientific Affairs Office of NATO.

Physical Properties of Inorganic Compounds—SI Units, A. L. Horvath. Published by Crane, Russak & Co., New York, 466 pages. In this book the essential physical properties of thirty one elements, and compounds which are needed by design engineers are presented in graphical and tabular form.

Statistics for Technology, Christopher Chatfield. 1975 reprint of Halsted Press, div. of John

Continued on page 75.

332 of our people left their jobs last year.



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ChE department

Worcester Polytechnic Institute And the WPI Plan

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Worcester Polytechnic Institute
Worcester, Massachusetts 01609

IF YOU HAD LOOKED in on the chemical engineering department at Worcester Polytechnic Institute (WPI) last January you might have seen the faculty members and their wives teaching "far-out" subjects ranging from natural childbirth (Imre and Barbara Zwiebel) and hatha yoga (Wilmer and Margaret Kranich), through Chinese gourmet cooking (Maria Ma) and pottery (Eileen Weiss) to championship table tennis (Yi Hua Ma and John Meader) and winter mountaineering (Bob Wagner and Joe Kohler).

Before you decide that chemical engineering education has gone completely astray under the WPI Plan, you should realize that these are mini-courses available during the two weeks of January Intersession along with such subjects as practical chemical manufacture (Zwiebel and Kranich), chemical plant trips (Stan Weinrich), or gas chromatography (Al Weiss).

Intersession courses are not required for a ChE degree at WPI; in fact no specific courses are required. The degree is obtained after satisfactory completion of four requirements.

- An examination which tests overall competency in the major field
- An independent qualifying project in the major field (MQP)
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- An independent qualifying project relating society and technology (IQP)

THE IQP

THE IQP, OR Interactive Qualifying Project is a new concept which brings learning about the technological society onto a personal level. While there is a tendency to take a ChE problem and evaluate its societal impact, such as "pollution control on the Nashua River" or "the effect of the petrochemical industry on Venezuela," often students approach this requirement from a non-departmental point of view. For example, teaching science in the secondary schools to special students involves the analysis of the problem (what makes the situation a special circumstance?), the development of a mode of attack (e.g., how to "turn students on" to chemistry) the execution of the plan, and the documentation. The final IQP reports are placed on the shelves of the WPI library, open to inspection by the public.

One innovative type of IQP takes a group of students to WPI's Internship Center in Washington, D.C. There under the overall guidance of a resident faculty member, the students work for seven weeks in teams assigned to various agencies, societies, or lobbying groups. The Washington experience is preceded by a time of preparation and followed by a time of reporting.

THE HUMANITIES SUFFICIENCY

THE HUMANITIES REQUIREMENT may in part be satisfied by passing a series of courses. These courses, however, have to be preselected to form a coherent, thematically related sequence. At the conclusion of this course sequence the students have to fuse together a selected topic, related to their theme, in an independent study seminar, and write a paper on the conclusions of the study. This approach, by design, emphasizes the study of a specific subject in depth rather than samplings of courses in each of the several humanistic studies. In a recent article in *EE* (Volume 66, Number 4, page 319, Jan. 1976) members of the WPI Humanities Department faculty described details of the Humanities Sufficiency, at least as it applies to history. Sufficiencies in art, English, history of science, philosophy, music, drama, and foreign languages are also available.

THE MQP

THE MAJOR QUALIFYING project (MQP) has already been discussed in this journal (*Chem. Eng. Educ.*, Winter, 1974). Students participate in a wide range of experimental, design, modeling, and theoretical projects: some work alone and some in groups. Some conduct their studies on campus and some at nearby industrial or governmental installations. The minimum effort by each student is equivalent to full-time activity for seven weeks. Most projects are devised in three approximately equal portions of preparation, execution, and reporting. At the end of the preparation stage the students usually write a project proposal describing the purpose and background of the project, outline their proposed method of attack, and anticipate their results with appropriate indication of the intended correlations. At the completion of the project the final reporting is often accompanied by an oral presentation. The written report is deposited in the WPI Library and is open for inspection to the public.

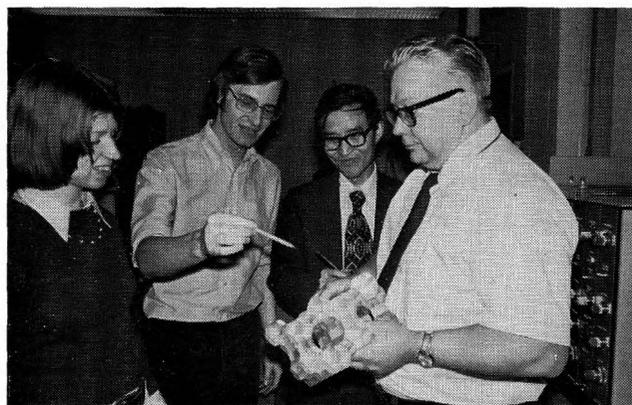
**Education at WPI
with its strong emphasis on
project work, and individual programs
and instruction, requires more faculty man-hours
than conventional methods.**

THE COMPETENCY EXAMINATION

EXPERIENCE WITH THE WPI competency examination was reported by Wil Kranich at the Fort Collins National Meeting of ASEE last year. This presentation is summarized below with additional material to bring it up to date.

The concept of a major examination shortly before expected graduation has long been in use in European universities. In the form employed at WPI, it is intended to test the readiness of the student to enter the profession. Thus it is not a collection of mini-final examinations in course work, but a major open-ended problem demanding a broad science background and engineering design creativity.

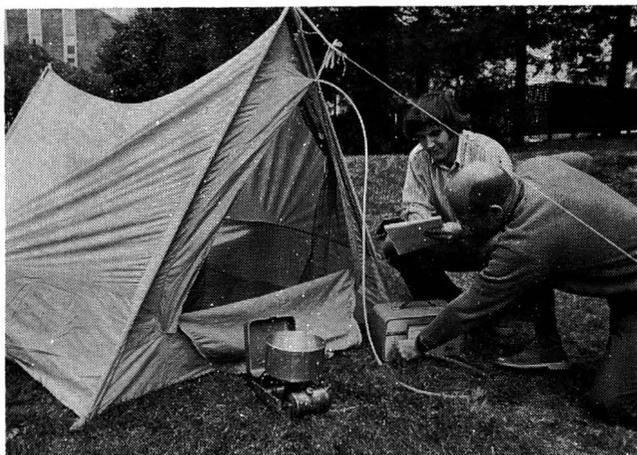
The objectives of the examination are taken from a departmental statement: "The professional preparation for chemical engineering has not been split into subspecialties, and thus graduates are expected to have an understanding of a rather broad field. Chemical Engineers entering the profession should have a capability for solving the problems of the chemical process and related industries, such as the creative, practical, and economical design of plants and individual component units of such plants. This requires the establishment of material and energy balances, the analysis of equilibria, and the evaluation of



French graduate students discuss structure of zeolite with Ma and Sand.

reaction rate and transport phenomena. Knowledge of physics and advanced chemistry, and the ability to solve problems involving differential equations is needed.

The competency examination tests the students' ability to solve problems that are based upon situations which might be encountered in industry by a beginning professional. The central thrust of the examination is on the broad competence which an industry or graduate school



Kohler and Wagner conduct test for carbon monoxide on back packers stove.

expects of all chemical engineers.”

In other departments at WPI, different examinations are provided for subdisciplines, such as materials engineering, power engineering or urban planning. In some cases individual examinations are especially designed for students with unconventional or interdisciplinary fields. For students who wish to be designated as chemical engineers, however, the same examination is presented to everyone taking it during any one period. Some optional questions are usually included to allow demonstration of particular competence in special fields.

The examination is made up by a departmental faculty committee of three, a different committee preparing each of the three exams given per year. Each exam is reviewed by the entire department before it is prepared in final form. The style of several examinations has been similar to that of the AIChE Student Contest Problems—an open-ended problem in an industrial setting. The four exams given so far have been based on:

- Copper smelting
- Coal gasification

- NOCl manufacture
- Single-stage production of adipic acid.

In each case the process involved has been new to the student, and considerable time is required to review chemistry and obtain background. For this reason the examination period is the maximum allowed by the college rules—one week.

Before a student may take any competency examination, he or she must be judged by the academic advisor as having appropriate preparation. This may be obtained by traditional course work, self-study in independent or guided learning, or by projects in appropriate fields.

After the written exam has been evaluated by the committee, the candidates have individual oral exams which probe more deeply in questionable areas. Each student's written and oral performance is judged as a whole and assigned a passing grade of “distinction” or “acceptable,” or is evaluated as “unacceptable,” in which case no record is retained.

After counseling by the examination committee and the student's advisor, and completion of appropriate remedial work, the unsuccessful student may take a later examination or, in rare cases, withdraw from the college. A few students, of course, change disciplines.

While it is too early to establish meaningful statistics on examination performance, it appears that about two thirds to three quarters of the students attempting any given examination receive passing grades. Faculty and student opinion based on recent examinations is that they achieve their objectives, but at high cost in time and stress on both examiners and candidates.

FACULTY INVOLVEMENT AND RESEARCH

E DUCATION AT WPI with its strong emphasis on project work, and individual programs and instruction, requires more faculty man-hours than conventional methods. Each set of competency examinations for example, requires several man-weeks in evaluation. Project advising is costly and can be brought to acceptable levels only when several students work on different phases of a single topic, or when industry bears a portion of the cost in off-campus centers (which still require intensive involvement by WPI faculty).

If each student took full advantage of the available flexibility of the program and built a

The IQP, or Interactive Qualifying Project, is a new concept which brings learning about the technological society onto a personal level, while there is a tendency to take a ChE problem and evaluate its societal impact, such as "pollution control on the Nashua River" or "the effect of the petrochemical industry on Venezuela." Often students approach this requirement from a non-department point of view.

unique interdisciplinary area of competence, the costs and logistics would become unmanageable. As might be expected, a majority of the ChE students is seeking general education along traditional lines. Even so, more than the usual effort is required of the faculty.

In spite of the demands of the undergraduate program, nearly all of the faculty are deeply involved in graduate education and research.

In addition to research projects in the areas listed in the attached table, some of the faculty are involved in other exciting projects. For example: Weiss coordinates a US-USSR cooperative program in formose reactions and, together with Kranich, supervises projects in catalytic detoxification of pesticides, and hydroliquefaction and gasification of solid wastes. Ma, in addition to his studies of multicomponent diffusion in porous media, conducts research in microwave vacuum freeze drying. Sand is investigating methods of synthesis and modification of zeolitic materials. Zwiebel is co-investigator of a binational research project dealing with the removal of sulfur from the products of coal gasification, and is concerned with the hybrid com-

puter solution of systems of partial differential equations. Kohler is studying the generation of methane from sewage and reactions of supported enzymes. Weinrich is working on the implementation of the department's newly acquired mini-computer in the process control areas and for data acquisition in the various research projects. The current level of industrial and governmental support of research exceeds \$200,000 annually.

The educational climate is greatly enhanced by frequent visitors to the Department, the active Colloquium Series with monthly presentations by ChE's in all walks of professional life, and visiting faculty and research associates from abroad. For example, during the 1975-76 academic year each of six foreign visitors spent six to ten months lecturing in courses and doing research in our laboratories.

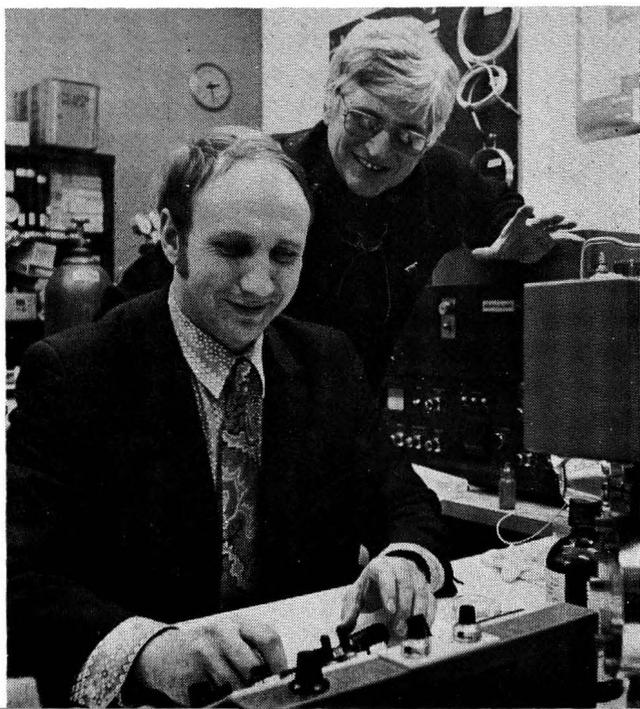
In addition to teaching, undergraduate projects, research and consulting, faculty members maintain high levels of professional standards. Membership in AIChE, ASEE, ACS, and other societies, regular attendance at meetings, participation in committees, as well as involvement in civic and community activities are important functions in the educational process.

We expect students to become acquainted with the faculty even outside the classroom. Facilitated by the projects, nearly individualized contact, often at the WPI Pub, is the rule rather than the exception.

The diverse non-professional activities of the faculty include frequent hiking expeditions led by Wagner and Kohler. In athletic competitions Stan Weinrich and Joe Kohler are the Departmental representatives on the tennis or basketball courts. Musical and artistic endeavors are fostered by Wil Kranich with his membership in the Worcester Chorus and the paintings and constructions which adorn his office walls. Zwiebel "wastes" his time with bridge, stamps, and talmudic scholarship. And, at last, the ingredients to good wholesome living will be provided by the newest

Continued on page 93.

Weiss watches visiting Russian scientist at console of interfaced chromatograph-mass spectrometer.



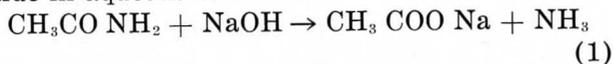
SAPONIFICATION OF ACETAMIDE IN A BATCH REACTOR

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IN DECEMBER 1974, Dr. E. O. Eisen reported at an annual meeting of A.I.Ch.E. the results of a survey he had made on the teaching of undergraduate kinetics [1]. Of those departments reporting the use of a laboratory experiment illustrating homogeneous kinetics, most utilized either (a) the hydrolysis of acetic anhydride or (b) the saponification of a carboxylic acid ester such as ethyl acetate.

We have refrained from the use of acetic anhydride by undergraduates because of the lacrymatory and vesicant action of this material. Our own experience with ethyl acetate, over a period of several years with students, is that the saponification proceeds so rapidly, even in dilute solution at room temperature, that quenching of the reaction for subsequent titration of unreacted base is difficult to conduct reproducibly. As a result, wide variations in rate constants were reported by different undergraduate groups in our laboratory, and attempts to determine an activation energy were hopeless failures.

The purpose of this note is to report some work, apparently successful in the hands of students, on another reaction that can be useful in an undergraduate chemical engineering laboratory. The reaction is the saponification of acetamide in aqueous solution:



The reaction is effectively irreversible and is second order.

Data on the second order rate constants are available in articles by Willems and Bruylants [2] and by Laidler and Chen [3]. Students are given these references in the laboratory instructions, with the note that the 1951 article is more directly useful for elevated temperatures. Interest-

ingly but not surprisingly, only one group of students has ever chosen to refer, in their laboratory report, to the article in French.

The saponification of acetamide is much slower than that of ethyl acetate, and it is convenient to conduct the reaction at modestly elevated temperatures, in the range of 40° to 80°C. This fact helps in quenching the reaction when aliquot samples are taken for analyses at room temperature. The large difference in rates is illustrated by the data of Laidler and Chen: at 25°C., the rate constant is $8.0 \times 10^{-2} \text{ l mole}^{-1} \text{ sec}^{-1}$ for the hydrolysis of ethyl acetate, and $3.77 \times 10^{-5} \text{ l mole}^{-1} \text{ sec}^{-1}$ for the hydrolysis of acetamide. The results of Willems and Bruylants on acetamide, obtained over the temperature range 65° to 85°C., lead to

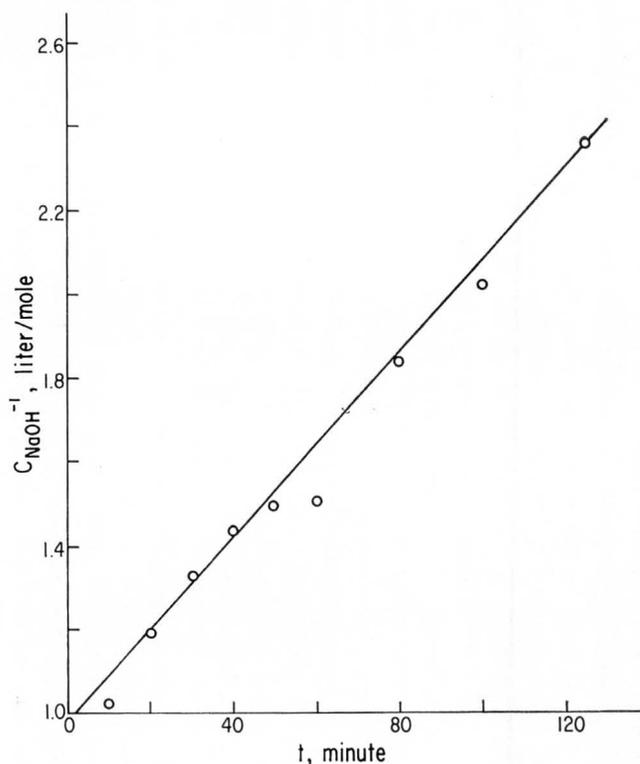
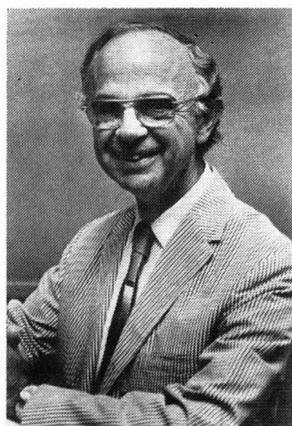


FIGURE 1. Second-order rectifying plot for the saponification of a cetamide at 47.5° C.



Sol Weller did his undergraduate work at Wayne and obtained his Ph.D., from the University of Chicago in 1941, under the Nobel Prize winner in physics, James Franck. After serving the N.D.R.C. and the Manhattan Project during W.W. II, he conducted research at the Bureau of Mines. He was head of fundamental research at Houdry Process Corp., then he joined the Aeronautic Division of Ford (later Philco-Ford). He came to SUNY/Buffalo in 1965 as professor of chemical engineering. He has contentedly pursued research in kinetics and catalysis in Buffalo since then, except for pleasant interludes as visiting professor at Berkeley, U.N. technical expert in Haifa, and Fulbright lecturer in Madrid.

the following expression for the rate constant:

$$k = 9.55 \times 10^5 \exp(-14,200/RT) \quad (2)$$

This is also consistent with the 25° value of Laidler and Chen.

We have found it convenient to use a solution that is initially 1M in both acetamide and sodium hydroxide, prepared by mixing equal volumes of the corresponding 2M solutions. The batch reaction is conducted in a multineck flask, immersed in a thermostatted water bath, and equipped with a variable speed stirrer; 0.1 N HCl and NaOH are used for the determination of unreacted NaOH in 2 ml. aliquots, removed periodically by pipette. Some feeling for the frequency of sampling can be obtained by observing that the half-time for reaction at 50°C., for an initial concentration of 1M for both reactants, is about 1.2 hr. Since the reactants are present in equimolar ratio, the rate constant is evaluated by any standard rectifying plot: e.g., $1/C_{\text{NaOH}}$ vs. t . Figure 1 shows such a plot for a run conducted at 47.5°C by a student group. The slope corresponds to a value of $k = 1.10 \times 10^{-2} \text{ l mole}^{-1} \text{ min}^{-1}$, or $1.83 \times 10^{-1} \text{ l. mole}^{-1} \text{ sec}^{-1}$.

Some of the important sources of error are:

- Preparation of the stock solution of acetamide by weighing directly from the bottle. Acetamide is hygroscopic. If concentration is to be determined by weight, the material should be

vacuum-dried first (m.p. = 82°C). Alternately, the concentration may be determined by allowing the alkaline hydrolysis with a known excess of NaOH to proceed to completion, with subsequent titration of residual alkali.

- Non-reproducible technique in the use of a 2 ml. pipette. (Practice with this might be educational for the chemical engineering student who lacks prior exposure to an analytical chemistry laboratory.)

- Failure to equilibrate the two initial solutions at reaction temperature before mixing.

One caution: NH_3 is slowly produced in the reaction. The laboratory should be adequately ventilated, therefore, especially when the reaction is run at temperatures above 50°.

ACKNOWLEDGEMENTS

The experimental data shown in Fig. 1 were obtained by Guy Jamesson and Mahmood Jawaid, whom the author was delighted to have as students. □

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2. Willems, M. and Bruylants, A., *Bull. Soc. Chim. Belg.* 60, 191 (1951).
3. Laidler, K. J. and Chen, D., *Trans. Far. Soc.* 54, 1026 (1958).

BOOKS RECEIVED

Continued from page 68.

Wiley & Sons, New York, 359 pages. The purpose of this book is to acquaint the reader with the increasing number of applications of statistics in engineering and the applied sciences.

Patterns of Problem Solving, Moshe F. Rubinstein. Published by Prentice-Hall, Inc., Englewood Cliffs, NJ, 544 pages. The material in this book was developed while teaching a campus wide interdisciplinary course, "Patterns of Problem Solving." The book attempts to provide the reader with tools and concept which are most productive in problem solving and are least likely to be eroded with the passage of time.

Thermoplastics - Properties and Design, Edited by R. M. Ogorkiewicz. Published by Wiley-Interscience, New York, 248 pages. This book sets out to provide an understanding of the principles underlying the properties of plastics, and also of the design problems associated with plastics in a way that will appeal to designers and engineers. □

INSTRUCTION BY THE PSI METHOD IN A REQUIRED SENIOR COURSE

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THE PSI METHOD of self-paced instruction introduced by Keller [1] has been gaining favor in higher education. Courses are being taught by this method at more than one hundred institutions. The National Science Foundation has sponsored PSI workshops, and the Center for Personalized Instruction was organized at Georgetown University in Washington, D.C. a little over a year ago. The American Institute of Chemical Engineers is becoming involved through the Modular Instruction Task Force—a subgroup of the CACHE Committee—sponsored by the National Academy of Engineering.

There are three important features of the PSI method—mastery orientation, self-paced study, and individual attention. Instruction is based on all students mastering all of the course material. How well this is achieved will be indicated by data showing the results from two years of the course operation. The students learn at their own rate from a textbook, from supplementary material prepared by the instructor, and by consulting with their fellow students and with staff members. The course material is divided into study units, and each student receives a study

As in many courses taught by the PSI method, a few lectures are given to stimulate interest and for general information. These lectures do not deal specifically with any of the course objectives.

guide for each unit. The study guide contains a list of objectives for the unit, a suggested study procedure, and some questions or problems. When the student decides that he has satisfied the objectives for a unit, he asks for a quiz. The quiz covers all the objectives of the unit. The quiz is graded immediately when the student finishes.

TABLE 1
CM416 Process Dynamics and Control

1. Ordinary differential equations
2. Feedback control systems
 - a. Conservation of mass and energy
 - b. Feed back
 - c. Block diagrams
3. Laplace transform techniques
4. First-order system response
 - a. Transfer functions
 - b. Time constants
5. Higher-order system response
6. Closed loop system operation
7. Control valves and controllers
8. Closed loop system response
9. Analog computer techniques
10. System stability
11. Root locus plots
 - a. Stability
 - b. Response

In order for a student to pass a quiz, the work must be entirely correct. The student is allowed to correct minor errors which he discovers during the grading process. If a student does not pass a quiz, another quiz covering the same objectives may be taken after a suitable study period. The instructor does not transmit information by lecturing and is free to help individual students who have learning difficulties or who have questions about the course material. These general features of the PSI method are often modified to fit the needs of individual courses or instructors.

At Michigan Tech, the PSI method was chosen for the process dynamics and control course, because it simulates the employment environment much more closely than does a course given using a lecture format. In an employment environment, people learn at their own rate by reading and by consulting with colleagues. The course in question is based on the text by Coughanowr and Koppel [2] and comprises the mixture of mathematics, response topics, and hardware topics usually covered in a ten-week term. A brief outline of the course is given in Table 1. This course is a required course for

senior ChE students. Since it is offered only once each year, students have good incentive to complete the course. In this respect, it is just like any other senior ChE course at Michigan Tech. This required course is followed by an elective course covering frequency response analysis, controller construction, and advanced topics. The elective course is taught using the normal recitation method, and there is a laboratory associated with it. The unit operations course is recommended as a prerequisite for the first course, but third year ChE students and electrical engineering students have completed the course successfully.

Tutors are available ten hours each week for quizzing and consultation. Students enrolled in the course usually are unable to use all of the available hours because of conflicts with other courses. There is a paid graduate teaching assistant to help with grading and course administration. Students enrolled in the course may also serve as tutors if invited to do so. The grading load is heavy, and assistance is necessary for

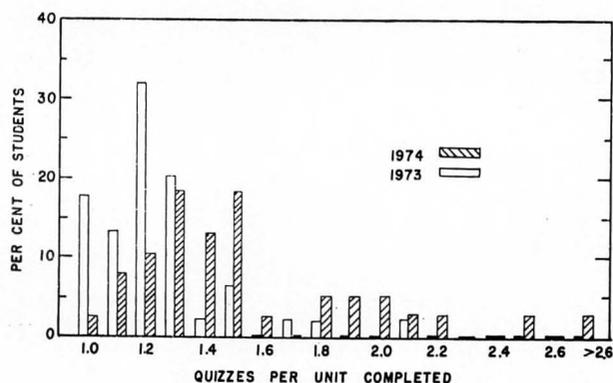


FIGURE 1. Frequency Chart for Quizzes per Unit.

smooth administration. More than 600 individual quizzes must be graded for a class of 40 students. This means that using the PSI method is quite time consuming. Figure 1 shows data for the number of quizzes taken per unit. Most students seem to take between 1.0 and 1.5 quizzes per unit. The mean was 1.2 in 1973 and 1.6 in 1974. This indicates some false starts but not too many. Students apparently are diligent in their study before requesting a quiz. They do not seem to take a quiz just to determine the nature of the questions.

A FEW LECTURES

AS IN MANY courses taught by the PSI method, a few lectures are given to stimulate in-

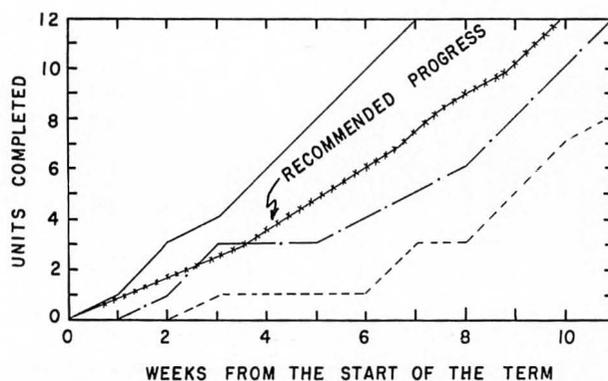


FIGURE 2. Progress Chart for Three Individual Students (1974).

terest and for general information. These lectures do not deal specifically with any of the course objectives. Typical lecture titles for the process dynamics and control course are "The Flyball Governor" and "The World Model." Only students who have completed a specified number of units are eligible to attend the lectures. About 50 percent of the eligible students attend the lectures. The rest prefer to work on the study units.

All course activities are terminated at the end of eleven weeks—ten weeks plus one week for final examinations. At the end of this time, all students must take the final examination, and all students receive a course grade. Having this constraint means that the course is not completely self-paced. The time limitation simulates a deadline which often occurs in an employment environment.

The wide variation in the rates at which individual students progress through the course is shown in Figure 2 where the progress charts for

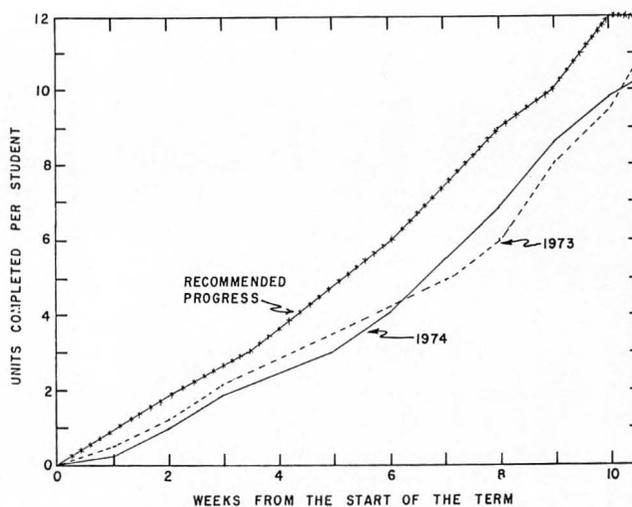


FIGURE 3. Mean Progress for the Class.

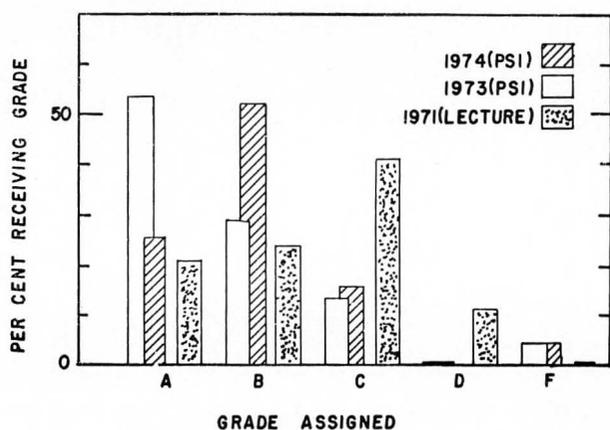


FIGURE 4. Grade Distributions.

three different students are plotted along with the recommended progress. The average progress for the class is shown in Figure 3 along with the recommended progress. It is typical of PSI courses that the average progress falls short of the recommended progress. For example, Philippas and Sommerfeldt [3] find this for an elementary physics course. The data in Figure 1 show one interesting thing. In 1973, no penalty was assessed for units completed late. General student opinion was that there ought to be a penalty for being late. In 1974, a mild penalty was established. The data for the average progress show that the penalty had little effect.

Grades are assigned according to the point scale shown in Table 2. An "A" is awarded if a student obtains 85 percent of the maximum

TABLE 2
CM416 Grading Scale

A+	200
A	171
B	128
C	96
D	63
F	63

number of points, a "B" if a student obtains 63 percent, a "C" for 49 percent, and a "D" for 31 percent. The system for awarding points is shown in Table 3. This point system seems to provide

TABLE 3
CM416 Point System

Pass a study unit	+10
Pass a study unit early	+1
Pass a study unit late	-1
Assist as tutor (2 hours)	+1
Final Examination	(Score x 68)
	<u>100</u>

a balance of incentive and penalties which stimulate most students to progress through the course at a reasonable rate. Having a penalty associated with passing a unit late means that the course is not truly a "Keller Plan" self-paced course.

INCREASED COMPETENCE

THE GRADE DISTRIBUTION data reported in Figure 4 show that there is an overall increased competence at the end of the course compared to the same course taught by the lecture method in 1971. The grade distributions show one effect of the penalty for completing units late. When no penalty was assessed in 1973, there were roughly twice as many A's awarded as B's. The

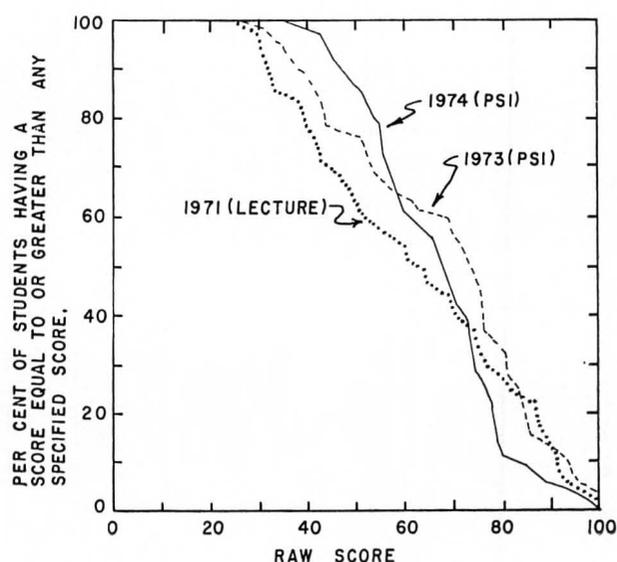


FIGURE 5. Final Examination Raw Score Distributions.

situation is exactly the opposite for 1974 when the penalty was begun. The grade distributions also show an effect which may be typical of required courses taught by the PSI method compared to required courses taught by the lecture method. For a PSI course, a greater number of students earn A or B than for a lecture course. For a PSI course, which is required in the curriculum, the number of students earning F is small but significantly greater than for a lecture course. It may be that in a lecture course students who have difficulty working independently will learn something just by attending class. These students will be unable to begin in a PSI method, can drop the course if they are unable to get started. The drop rate for the required process dynamics and control course is between six and twelve percent

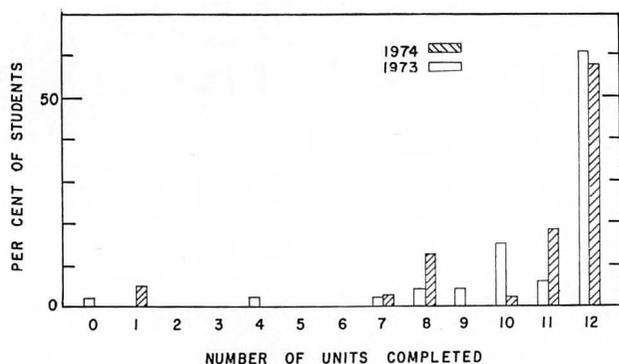


FIGURE 6. Frequency Chart for the Number of Units Completed.

compared to a 29 percent drop rate for a senior biological sciences elective course and a 20 percent drop rate for the required dynamics course offered in the sophomore year. [4] Both the latter courses are taught using self-paced methods. For the dynamics course, students also have the option of taking the course by the lecture format.

For the process dynamics and control course, the final examination is a comprehensive examination covering a sampling of all objectives. The score counts a little more than one-third of the final grade. The raw score distributions for the PSI course and the lecture course are compared in Figure 5. Nearly the same final examination was given for both courses. However, the examinations for the PSI courses covered somewhat more material and were closed book examinations. The examination for the lecture course was an open book examination. These data show that students who have studied by the PSI method do just as well if not better on written examinations as do students who have studied by the lecture method. In the range of raw scores between 30 and 75, the students who studied by the PSI method had generally higher scores than the students who studied by the lecture method. In the higher range and the lower range of raw scores, there does not seem to be much difference between the two groups.

In Figure 6, frequency data for the number of units completed by the end of the course are shown. Most students complete eleven or twelve units in the time allotted for the course. Comparing the data for 1973 (no late penalty) and 1974 (late penalty) shows again that the penalty for passing a unit late has no significant effect.

Correlations of final examination score with number of units completed presented in Figure 7 show that lower examination scores are typically

associated with a smaller number of units completed though there is considerable scatter. The examination grades range downward from the perfect correlation line passing through the origin and a raw score of 100 for a student completing all twelve units. The data presented in Figure 8 show that no student who completed all units earned a "C" and that no student who did not complete all units earned an "A".

QUESTIONNAIRE RESULTS

AN OPINION questionnaire was employed during 1973 and 1974 to obtain student ideas about the course. Students generally feel that the objectives are clear and related to other courses and to professional practice. They are favorably disposed toward the textbook, the quizzes, and the

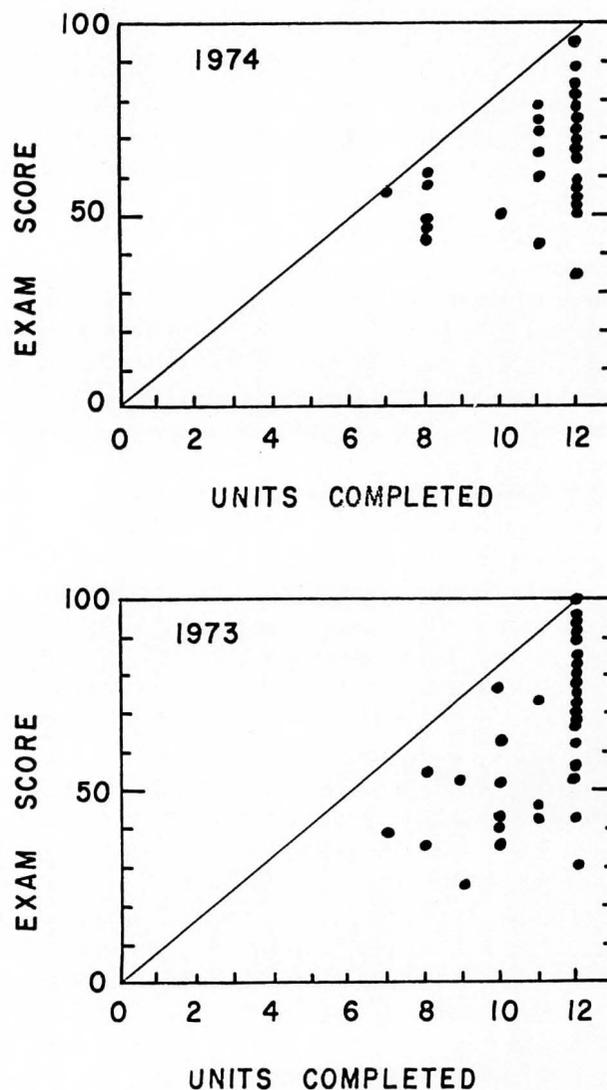


FIGURE 7. Examination Score Correlations.

Continued on page 101.

AN IVORY TOWER MAN DINES IN THE REAL WORLD

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THE FAMINE

BECOMING A UNIVERSITY professor immediately after receiving a doctorate degree can be an uneasy experience. All those years in graduate school flood the mind with differential equations and FORTRAN programs. Boundary layers, laplace transforms and digital computers become a way of life. Little time is spent worrying about why pumps cavitate, why heat exchangers leak, why bearings fail, why pipelines corrode away or why reactors plug. Even less time is devoted to solutions to the above problems. The reason is simple. Popular text books rarely discuss them. Chemical engineers with bachelor's degrees are confronted with these problems daily. A useful education for them demands that their instructors know the answers to such questions and relate the importance of such "mundane" problems.

Graduate students on assistantships or fellowships seldom worry about financial red tape. Their advisers take care of that. The paycheck somehow gets home every month. The student researcher's mind can't be cluttered with priorities, justifications, budget estimates, transfer of funds and similar monetary considerations. In industry, making a profit for stockholders is the primary justification for existence. How money is handled determines whether it's a steak or hamburger year. Engineers must help decide how much and where money is spent. Instructors who don't know can't tell students.

The above paragraphs are not meant to unduly criticize the educational system per se. The point is that industrial experience is essential for any instructor who is preparing students for an engi-

neering career outside research. Getting this experience without giving up teaching altogether is a difficult task in many universities.

FOOD FOR THE HUNGRY

THE AMERICAN SOCIETY for Engineering Education (ASEE) sponsors a Resident Fellow Program just for engineering faculty wanting 12-15 months industrial employment. Research work is discouraged and "real-life" experiences are top priority. Industry pays the Fellow's wages, while ASEE picks up moving expenses from and to the university. Employment depends on company/faculty match of interests. Luckily, Standard Oil Company of California was willing to hire this writer.

Few of the problems discussed required extensive calculations for their solution. Some of the day-to-day problems, however, do require mathematical treatment.

THE MENU

WORKING IN A LARGE industry for one year (365 days in this case) can be handled in different ways. The Fellow can spend short periods of time in many different areas, thereby gaining lots of superficial knowledge about an entire complex operation. Benefits to the Fellow are many but the employer gets little return for his investment because time spent in any one area is too short. A second approach is to treat the Fellow as an ordinary employee and have him become intimately familiar with one or two plants. He may

not see the entire manufacturing complex but should be quite valuable to the company before he leaves. Other options such as assignment to detailed design projects are also available. Personal preference of the Fellow and company needs determine the final choice.

HORS D'OEUVRES

Before an engineer can do meaningful work for a company, he must learn a few things about the firm or unit where he is employed:

- Where is technical information located? (Don't underestimate the yellow pages!)
- Who are the company experts in specialized areas?
- How are equipment files organized?
- What paper work is required to get work done in the field?
- Who sets priorities on field work?
- How are materials ordered and delivered?
- How are contracts written, approved and executed?
- What are the safety requirements set by the company?
- How is money obtained for expensive maintenance projects?
- What levels of approval are needed for capital expenditures?
- What are the lines of communication, i.e., who is supposed to know what you're doing?

Answers to all these questions will vary from company to company, but they are facts which every engineer needs.

THE MAIN COURSE

MOST OF THE JOBS discussed below were problem types assigned to the author or any engineer in manufacturing. Some solutions are given. At times no solutions were found. None of the work items were textbook problems with answers in the appendix. They are discussed briefly in order to show future Fellows the variety of problems to which they can be exposed. Industrial readers should note that a Ph.D. doesn't immunize an engineer from dirt and grease. Student readers will guess that even professors can't solve all their problems.

Leaks around stems and bonnet gaskets of valves are never-ending problems. Replacing packing and gaskets is straightforward if the valves can temporarily be taken out of service. New sealing materials are often tried on repeaters. Grafoil (a patented Union Carbide form of graphite) is the latest wonder product in many applications. On occasion, a leaking valve can shut down an entire plant if it can't be isolated. Other times, spe-

cial clamps must be designed so a heat-setting material (like Copaltite) can be pumped inside the clamp to surround the leak. As the Copaltite sets up it stops the leak. (This solution works only on valves handling hot stock . . . that should have been obvious).

Erosion/corrosion of trim in valves can be tough to stop. Deciding if corrosion is the primary factor often requires detailed metallurgical analyses. Materials selection is not a cut-and-dried procedure. Exotic materials are expensive (carbon steel is getting that way) and may not give appreciably longer life. Past experience can be the best guideline. When erosion is the real problem, hard-surfacing the wearing parts may be the answer. Other times, changing the style of trim will

A useful education for B.S. ChE's demands that their instructors know the answers to such practical questions and relate the importance of such "mundane" problems.

help. Really bad cases require replacing the entire valve with one of suitable trim and material.

Piping flange leaks have many causes but no cheap solutions once they start. The most common cause is dirt on the sealing surfaces. Poorly made gaskets and improper bolt-up are other culprits. Short spools which don't line up perfectly in tight spaces can induce strains which prevent proper seating of the gasket. Also, designers sometimes follow codes too explicitly so that not enough extra "beef" is available. As a result flanged joints can't take the strain for a variety of reasons and leak. The unfortunate cure for many leaks is to shut down a large section of a plant until the gasket can be replaced or the seating surfaces remachined or the piping system modified. Once in a while a special clamp plus Copaltite will seal off the leak. If a particular flange leaks repeatedly after start-ups, it's time to consider a new-style gasket. In extreme cases, flanges may be welded or removed and replaced with a straight piece of pipe.

Seal and/or bearing failures in pumps, turbines or compressors are frequent headaches. Friday evening is the most common time for these occurrences. Improper type of lubricating oil is seldom the problem. Misalignment, inadequate flush to the seals or too little oil circulation to the bear-

ings is the usual cause. Old age is another if a pump gets overlooked on the maintenance schedule. Cures range from in-kind replacement to complete modification of the seals and seal flush system and/or oil lubrication system.

Few of the problems discussed so far required extensive calculations for their solution. Some of the day-to-day problems, however, do require mathematical treatment. Sizing pipelines for vents or recycle streams is a familiar calculation. Calculating maximum operation temperatures for reaction vessels is done periodically, particularly if part of a refractory lining has been changed. Operating temperatures are normally limited by temperature limits on the shell as set by ASME code requirements. Changing ranges on flow meters and resizing control valves are among the most common calculations made.

Energy conservation is even more critical now than in the past. Seemingly small items like recovering condensate from steam traps add up to many dollars in a large plant. Critical evaluation of blowdown systems in plants with several steam boilers can show ways of generating more steam without consuming more fuel. Since furnaces are large consumers of fuel, careful control of fuel/air ratios (e.g., by installing stack dampers) is always economically attractive. Igniting a smoke bomb in furnaces (whose stacks can be sealed off) when they are shut down will show where leaks may exist in the stacks or other seams of the furnace. Unwanted air may leak through the openings during operation.

Noise pollution is a real concern, particularly if a plant is close to a residential area. Valves,

**In graduate school . . .
little time is spent worrying about
why pumps cavitate, why heat exchangers
leak, why bearings fail, why pipelines
corrode or why reactors plug.**

compressors and furnaces are all contributors. For new systems, designs can incorporate "quiet" equipment. In existing plants, reducing noise by lagging pipe or adding burner mutes to furnaces is an expensive and marginally effective solution in most cases. In this relatively new field much work remains to be done.

Major projects (those with budgets > \$50,000) consume about one-third of an engineer's time the

first year. Probably the most emotional of projects—and best learning experience—is being a shutdown engineer. Preparing a worklist and ordering materials begins two to three months in advance (or sooner now because of material problems). The actual time a plant is down while equipment is being dismantled depends on the size of the plant and the amount of work to be done. Meeting deadlines is a real challenge. Dealing with the unexpected is the most exciting aspect of the job. The success or failure of a shutdown engineer depends largely on his ability to deal with people on the spur of the moment. There is no time to look in a favorite reference book or cite famous literature articles. Getting critical materials to the plant site in a hurry is a fun task. Transportation costs often exceed the price of the material. Cannonball express is a very descriptive phrase. A truck can be hired to drive up to 100 miles from the plant to pick up something as small as a valve bonnet gasket. Justification for such delivery expenditures is simple. Every hour that the plant is shut down beyond the schedule costs hundreds or even thousands of dollars in lost production.

The educational (in a textbook sense) part of a shutdown is seeing internals of all the equipment discussed functionally in lectures. No picture can give the same effect as actually seeing it in person. It's a real eye-opening experience to see an exchanger bundle covered with carbon particles and then find out it was still operating satisfactorily. Equally amazing is seeing a pump impeller corroded so badly it begins to crumble when touched—and then verifying that it was still pumping sour water.

Materials availability and price spirals challenge the best cost estimators. Small amounts of rare metals like Incoloy 825 or Inconel 600 are located in very obscure places. Finding them gives Ma Bell a real shot in the arm. For large amounts, no price can get deliveries speeded up. Companies just wait their turn. Previously abundant things like refractories are being added to the scarce list. Even Tokyo can't supply some varieties in less than three months.

DESSERT

BESIDES DOING ENGINEERING work, Fellows are exposed to management philosophies and actions through informal luncheons (free!) or committee meetings. Safety, pollution and public relations are high-priority items. The dollars spent to modify equipment which offends nearby

Industrial experience is essential for any instructor who is preparing students for an engineering career outside research. Getting this experience without giving up teaching altogether is a difficult task in many universities.

residents is nearly unbelievable. Such expenditures seldom show a return on investment.

Working for an oil company during the energy crisis and Arab embargo was prime time for observing management and publicity men in action. Statistics in newspapers can be very misleading unless they show the whole picture. Getting both sides of the story certainly cleared a lot of fog. Knowing the oil companies' views makes one a believer in energy conservation.

A LITTLE ALKA SELTZER

HHEADACHES WERE FEW, but some helpful hints seem in order for future participants to make thinks even smoother.

Industry—forget the Fellow has a Ph.D. This can actually be a handicap. He probably hasn't had his hands dirtied by anything more than carbon paper on computer printout. Grafoil gaskets, John Crane 187-I packing, dum dum, Copaltite and Locktite are still Greek the first few weeks. Maintenance people are hard to convince that a doctor doesn't know everything. Bachelors are more easily forgiven for their "ignorance." Keep the man busy. Boredom quickly discourages even the most enthusiastic engineer.

Fellows—don't brag about having your doctorate. A 50-year-old machinist with 30 years experience knows a lot more about his plant than any book will tell you. Just because a man is old, don't assume he's senile. An experienced pipefitter can help you out of more piping problems than any Reynold's Number-Friction Factor Chart. On the other end, don't think a man your age without a college education must be dumb. Listen to what he has to say—in fact, ask his opinion, then *think* about it. The more people you ask the more apt you are to find the real problem and then its solution. Don't be afraid to admit you were wrong and a less educated person was right. Only God never makes mistakes. Don't fret if all your fancy calculations say something should work, but it doesn't. (Molecules sometimes refuse

to be ideal gases). Quite often there is no substitute for "gut reaction" engineering. You did it because deep down inside it felt good. Very few equations have a symbol for common sense, even though it is the most important factor in many solutions.

Above all, don't expect to acquire a portfolio of problems which can be used as classroom exercises. Such is not the point of the program. The non-cookbook problems are most important for rounding out your education. Many will be interesting tales to relate during lectures but won't be amenable to solution with an HP-35.

Life in industry won't be a bed of roses. Some days are boring; others are frightfully frustrating. Most, however, can be quite enjoyable with the proper attitude.

MINTS ANYONE?

LITERATURE ON THE Resident Fellow Program seems to reach universities through engineering education magazines. Unfortunately, several large chemical companies were contacted by the author and had never heard of the idea or were not actively involved in it. Benefits to industry are not just the work a Fellow performs. Good relations can be established with a university and communication lines are opened to express criticism of graduates and suggest improvements in engineering curricula. These thoughts can be conveyed during, as well as after, the residency.

Future success of the Residency Program will depend on greater support by industry. A modification worth exploring would be to set up an exchange program whereby someone from industry replaces the faculty member at the university. Caution: University pay scales are significantly lower than industrial ones.

GRATUITIES

The author wishes to express his sincere and long-lasting thanks to the many employees of Standard Oil Company of California, who made life easier when he didn't yet know which fork to use. Thanks also goes to the American Society for Engineering Education for picking up part of the tab for this most worthwhile experience. □

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PACKED COLUMN MASS TRANSFER COEFFICIENTS FOR CONCURRENT AND COUNTERCURRENT FLOW: AN ANALYSIS OF RECENT WORK

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THERE ARE CERTAIN advantages to concurrent as opposed to countercurrent flow. The concurrent liquid flow rates need not be as high as those in countercurrent flow. As a consequence, lower pressure drops over the packed column are found in concurrent flow. Flooding, a change from gas-continuous liquid-dispersed to liquid-continuous gas-dispersed operation, will not occur in a concurrent operation. Although a large uniform concentration difference is more easily maintained in countercurrent flow, a gas-liquid reaction can create the same absorption concentration difference even under concurrent flow conditions. The following four papers present recent concurrent flow research.

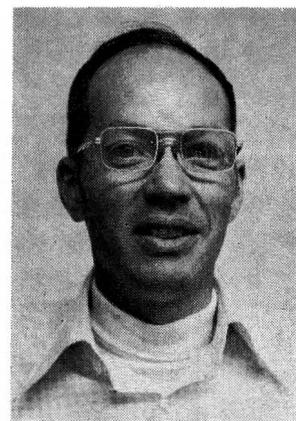
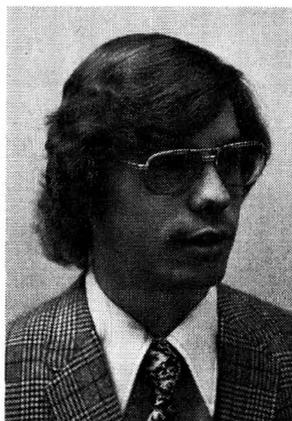
Dodds, Stutzman, Sollami and McCarter (1960) studied the absorption of carbon dioxide by caustic solutions. This was done with concurrent flow and minor liquid partial pressures, but only over-all coefficients, $K_g a$, were reported. They found that above the 99% significance level, temperature, liquid and gas flow rates, and the type of packing were the only parameters that affected $K_g a$. Their study showed that only under certain conditions was concurrent flow more advantageous.

Wen, O'Brien and Fan (1963) studied the air-water and air-2.5N Na_2CO_3 systems in concurrent flow using different liquid and gas flow rates, and various packings. They obtained pressure drop as a function of the above parameters in an empirical expression of the form $\Delta P = a(L-b)^c + d 10^{eL}G$. The constants a, b, c, d and e must be evaluated for each packing, as well as for different fluid properties. However, this form

could not be directly extended into other packing or fluid systems without further investigation.

Reiss (1967) obtained ammonia absorption and oxygen desorption mass transfer coefficients for concurrent gas-liquid contacting in packed columns. The experimental mass transfer coefficient for oxygen desorption at 77°F within $\pm 25\%$ is $K_l a = 0.12(E_l)^{1/2}$ where E_l is the energy dissipation per unit volume, $V_l(\Delta P / \Delta Z)_{lg}$. He obtained a similar expression for ammonia absorption, but as $k_g a = 2.0 + 0.91(E_g)^{2/3}$. Although these correlations are for mass transfer coefficients and particular systems, they are not good over extended regions of liquid and gas flow rates.

The system studied by Ufford and Perona (1973) was one in which gas (CO_2) was



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transferred from a moving gaseous phase (CO₂-air) into a concurrent liquid phase (H₂O) in which it is slightly soluble. In this system, as the two phases move through the column, the concentration of the gas in the liquid phase increases because after the gas enters the liquid, no significant reaction takes place.

CONCURRENT FLOW DEVELOPMENT

BECAUSE OF THE RELATIVE inexperience chemical engineers have had with concurrent flow in packed column applications, it is appropriate to develop the mass transfer equations that apply in this situation. The development presented here follows that of Ufford and Perona (1973) and, therefore, applies directly to systems of gas-liquid absorption without significant chemical reaction.

In terms of measurable concentrations, the rate of transport of the gas into the liquid per unit area of contact, N , times the local interfacial area per unit volume of column, a , can be given by

$$Na = k_x a (x_i - x) \quad (1)$$

for the liquid, and

$$Na = k_y a (y - y_i) \quad (2)$$

for the gas. The mass transfer coefficients in the liquid and gas phases are given by k_x and k_y , respectively. The units of k_x and k_y are moles per time per area per concentration differences. Ufford and Perona (1973) and others have assumed that the interfacial concentrations, y_i and x_i , are in equilibrium and can, therefore, be related to Henry's Law, $y_e = (H/P)x_e$, where H is the law constant and P is the total pressure of the system. The interfacial concentrations, y_i and x_i , are equilibrium concentrations, and, therefore, correspond to equal chemical potentials of CO₂ in both phases at the interface (Treybal, 1968).

Since the interfacial concentrations are not measured practically, a more useful relation employing the bulk phase concentration, x^* , can be used. In terms of the bulk liquid phase concentration

$$Na = K_x a (x^* - x) \quad (3)$$

where K_x is the over-all mass transfer coefficient. This can be used because x^* is related to the bulk gas phase concentration, y , through the equilibrium relationship. This allows conditions in both phases to be included in the expression for Na .

There is also a relationship between the in-

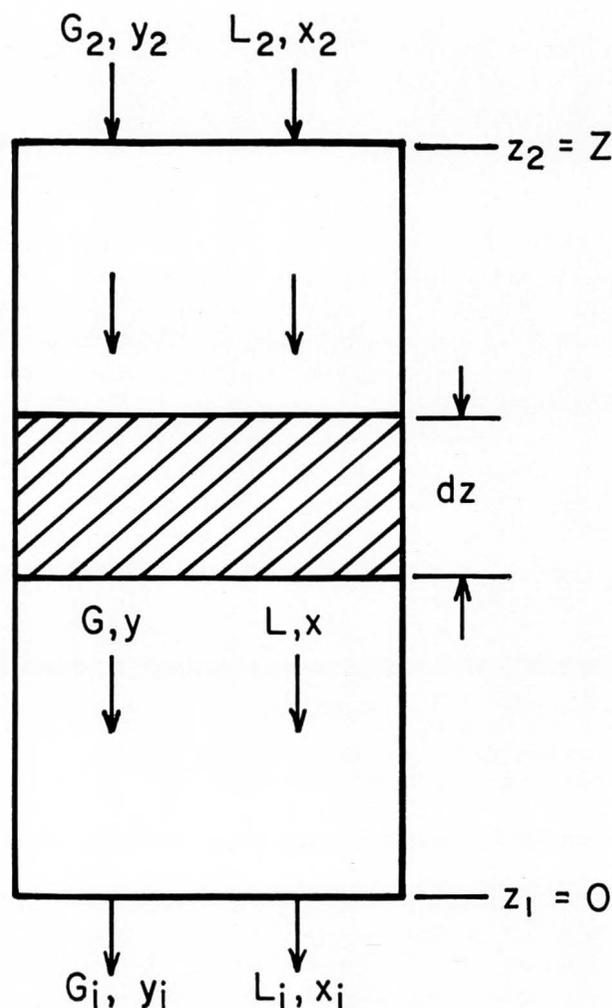


FIGURE 1. Concurrent flow packed column model.

dividual phase coefficients, k_x and k_y , and the overall mass transfer coefficient. Equation (1) can be arranged to give

$$\frac{1}{k_x a} = \frac{(x_i - x)}{Na} \quad (4)$$

Substituting Henry's Law, $x_i = (P/H)y_i$ and $x^* = (P/H)y$, and $(x_i - x) = (x^* - x) + (x_i - x^*)$, Equation (4) becomes

$$\frac{1}{k_x a} = \frac{(x^* - x)}{Na} + \frac{(P/H)(y - y_i)}{Na} = \frac{1}{k_x a} + \frac{P}{Hk_y a} \quad (5)$$

Equation (6) represents the over-all resistance to mass transfer in terms of the individual phase resistances.

In systems where the gas phase is slightly soluble in the liquid phase, Henry's Law constant will be large. It can therefore be assumed

that there will be negligible resistance in the gas phase. Therefore, the liquid phase resistance would be controlling the absorption process, and therefore Equation (6) may be written as

$$\frac{1}{K_x a} \cong \frac{1}{k_x a} \quad (7)$$

Equation (7) was checked and verified by Ufford and Perona (1973) using a trial and error procedure; however, no specific details of the procedure were given. This relation has also been verified elsewhere (Koch, Stutzman, Blum and Hutchings, 1949).

Using experimental data an expression for $K_x a$ can be found. Consider a differential section of packed column as shown in Figure 1. It is assumed that k_x and a are the same in all parts of a packed column. The validity of this assumption depends primarily on the packing size to

There are certain advantages to concurrent as opposed to countercurrent flow.

column diameter ratio. If the column height is more than a few times the column diameter, channeling usually occurs. While operating at steady state, the change in the amount of solute per unit time in the liquid phase in a differential section, $\epsilon d(Lx)$, is equal to the transfer of solute into the liquid phase per unit time, $K_x a(x^* - x) \epsilon S(-dz)$. Since the amount of solute in the liquid phase at any point, Lx , increases in the negative z direction, a negative dz must be used. In equation form, without the differential increment, the above statement can be written as (Van Winkle, 1968, p. 619):

$$d(Lx) = K_x a(x^* - x)S(-dz) \quad (8)$$

To determine the relationship between x^* and x an operating line must be derived which expresses the equilibrium phase concentrations over the entire column. To obtain the operating line a molar balance (no reaction) is written over the top of the column and the differential section. This balance may be written as

$$x_2 L_2 + y_2 G_2 = xL + yG \quad (9)$$

When there is no reaction and the gas is slightly soluble, the changes in the liquid and gas flow rates are negligibly small. The flow rates can

therefore be assumed approximately constant, thus $G_2 \cong G$ and $L_2 \cong L$. Equation (9) may then be written as

$$y = (L/G)(x_2 - x) + y_2 \quad (10)$$

From Henry's Law, the bulk gas phase concentration, y , would be in equilibrium with the bulk phase concentration, x^* , and thus $x^* = (P/H)y$. Combining this with Equation (10) yields

$$x^* = (P/H)(L/G)(x_2 - x) + (P/H)y_2 \quad (11)$$

Reiss (1967) also used this equation for absorption. Defining $(L/G)(P/H) = A$ as a constant and substituting Equation (11) into Equation (8) yields, since L is approximately constant,

$$Ldx = K_x aS(A(x_2 - x) + x_2^* - x)(-dz) \quad (12)$$

Solving for dz and integrating yields

$$\int_{z_1}^{z_2} -dz = -Z = \frac{L}{K_x aS} \int_{x_1}^{x_2} \frac{dx}{(Ax_2 + x_2^* - (1-A)x)} \quad (13)$$

With $x_2 = 0$, integration of the right side of Equation (13) yields

$$-Z = \frac{-L}{K_x aS(1+A)} \ln \frac{x_2^*}{x_2^* - (1+A)x_1} \quad (14)$$

Solving this equation for the over-all mass transfer coefficient gives

$$K_x a = \frac{L}{ZS(1+A)} \ln \frac{x_2^*}{x_2^* - (1+A)x_1} \quad (15)$$

$K_x a$ or $k_x a$ can be calculated directly from experimental data using this equation.

From Equation (13) the over-all height of a transfer unit (HTU) for the liquid phase is seen to be

$$H_{OL} = \frac{L}{K_x aS} \quad (16)$$

and thus, the over-all number of transfer units (NTU) is

$$N_{OL} = \int_{x_1}^{x_2} \frac{dx}{(Ax_2 + x^* - (1+A)x)} \quad (17)$$

such that

$$Z = N_{OL} H_{OL} \quad (18)$$

From Equation (15) it can be seen that

$$N_{OL} = \frac{1}{(A+1)} \ln \frac{x_2^*}{x_2^*(A-1)x_1} \quad (20)$$

In comparing Equations (19) and (20) it is apparent that the only differences are the negative 1 in the (A-1) term and the + sign in the denominator of the ln function. This is due to the gas stream flowing in the positive z direction.

DISCUSSION

THE FOLLOWING discussion will now compare the relative magnitudes of concurrent and countercurrent mass transfer coefficients. For proper comparison, only research on similar systems will be used.

Ufford and Perona (1973) experimented with 3/4-inch Berl saddles, and 1/4- and 1/2-inch Raschig rings using liquid flow rates up to 66,100 lb/hr-ft² and gas rates ranging from 43 to 120 lb/hr-ft². Their experiments were done in concurrent flow, using the CO₂-air-water system.

They fit their experimental data to a model

that is represented in the form $k_x a = k_x a = CL^r G^s$. The coefficient and exponent values for the model for each type of packing are shown in Table 1.

TABLE 1. Correlation Parameters
(Ufford and Perona, 1973)

Packing Type:	C	r	s
3/4-inch Berl Saddles	7.78	0.82	0.46
1/2-inch Raschig Rings	3.59	0.93	0.42
1/4-inch Raschig Rings	4.23	1.06	0.75

Although the values for the coefficients in Table 1 are said to be well representative, the authors do not indicate how representative. A statistical parameter such as r², indicative of fit, would have been appropriate. Their results for k_La, using Raschig rings compared with other workers' results are shown in Table 2. These results are for various packed heights, gas rates and liquid rates. The liquid flow rate power dependence is also given for comparison purposes.

TABLE 2. Liquid Phase Mass Transfer
Coefficients: k_La (lb/hr-ft²)

SOURCE	1	2	2	3	4	2	2	5	6	4	2	4	2	
SYSTEM	1	2	2	2	2	2	2	2	3	4	2	2	2	
FLOW	CTC	CNC	CNC	CTC	CTC	CNC	CNC	CNC	CNC	CTC	CNC	CTC	CNC	
PACKED HT.	12"	10"	10"	3.36'- 4.34'	13.2"	10"	10"	0-75"	12'	15.3"	10"	17"	10"	
PACKING	1	2	3	4	3	3	3	3	5	6	7	8	7	
G ($\frac{lb}{hr-ft^2}$)	58	58	58	18.75- 84.3	100	100	150	30- 1380	46.4- 125.4	100	100	230	230	
L ($\frac{lb}{hr-ft^2}$)	1500	1710	438	541	1090	2017	680	806	1050	680	1730	547	2479	1660
	2000	1997	594	707	1436	2434	888	1050	1360	906	2130	692	3051	2101
	3000	2434	913	1030	2120	3166	1295	1630	1990	1360	2870	965	4084	2930
	4000	2883	1238	1346	2793	3817	1692	2006	2587	1810	3510	1222	5036	3709
	6000	3607	1903	1963	4122	4967	2467	2930	3910	2721	4700	1704	6741	5172
	8000	4087	2582	2565	—	5989	3224	3640	5340	3620	5785	2157	8044	6548
	10,000	4692	3271	3156	—	6924	3968	4703	6900	4530	6890	2590	9718	7863
	0.54	1.06	0.93	0.96	0.65	0.93	0.72	0.99	1.00	0.72	0.82	0.72	0.82	

SOURCES

- Allen (1938)
- Ufford & Perona (1973)
- Koch et al (1949)
- Sherwood & Holloway (1939)
- Reiss (1967)
- Danckwerts Gillham (1966)

SYSTEMS

- CO₂-Water
- CO₂-Air-Water
- O₂-Air-Water
- CO₂-0.5M Na₂SO₄

FLOW

- CTC—Countercurrent
CNC—Concurrent

PACKING

- 3/8" Raschig Rings
- 1/4" Raschig Rings
- 1/2" Raschig Rings
- 3/8"-1 1/4" Raschig Rings
- 1 1/2" Raschig Rings
- 1/2" Berl Saddles
- 3/4" Berl Saddles
- 1" Berl Saddles
- 3/4" Berl Saddles

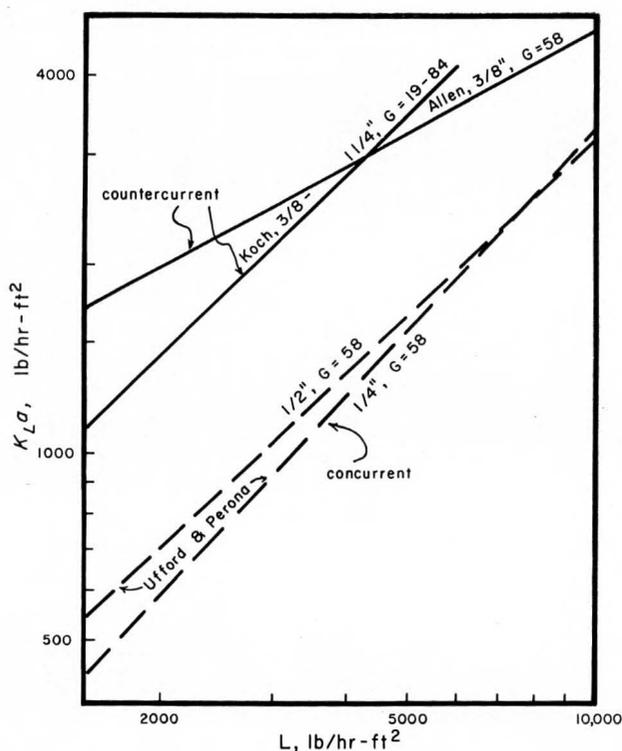


FIGURE 2. Mass transfer coefficients for Raschig rings at lower gas mass velocities in CO₂-air-water systems.

Comparisons between the concurrent and countercurrent results tabulated in Table 2 are more readily seen in Figures 2 to 4. Sherwood and Holloway (1939) ran countercurrent flow experiments on the hydrogen-, oxygen- and carbon dioxide-water system using 0.5-, 1.5- and 2.0-inch Raschig rings. The gas flow rates ranged from 30 to 1300 lb/hr-ft², and liquid flow rates varied from 200 to 32,00 lb/hr-ft². Comparison of 0.5-inch Raschig rings between Sherwood and Holloway, and Ufford and Perona at various liquid flow rates are shown in Table 2. A gas flow rate of 100 lb/hr-ft² is used because Sherwood and Holloway used this as their only gas flow rate for 0.5-inch rings. As shown in Table 2, the L dependence from the correlation of Sherwood and Holloway for 0.5-inch rings is 0.65. Ufford and Perona found a dependence of 0.93. The countercurrent liquid mass transfer coefficients are greater by factors of about 3 at the lowest liquid flow rate and about 1.75 at the highest liquid flow rate. This is notable because the same mass transfer coefficients are attainable at very high liquid flow rates if extrapolation is allowed. This liquid flow rate for matching mass transfer rates is above the countercurrent flooding point of approximately 13,300 lb/hr-ft².

For 1.0-, 1.5- and 2.0-inch Raschig rings, Sherwood and Holloway found a liquid flow rate power dependence of 0.72, but this was using gas flow rates of 100, 230 and 230 lb/hr-ft² for each packing, respectively. They did not vary enough gas flow rates for each type of packing; therefore, gas rate dependence is undetermined. Packing height was varied from 6 to 49 inches with no effect on the mass transfer coefficient. Ufford and Perona stated that Sherwood and Holloway correlated data on 0.5-inch Raschig rings from Allen (1938). Allen experimented with 3/8-inch rings only. Allen found a liquid flow rate power dependence of 0.54 for a gas flow rate of 58 lb/hr-ft². This dependence was determined by Sherwood and Holloway using their correlation model. A comparison between the data of Allen and that of Ufford and Perona is shown in Table 2. The countercurrent mass transfer coefficient is 3.16 and 3.91 times larger than the concurrent coefficients for 1/2- and 1/4-inch rings, respectively, at the lowest liquid flow rate. This compares with a countercurrent coefficient that is 1.43 and 1.49 times larger at the highest liquid flow rate. After an L of about 14,000 lb/hr-ft², a concurrent tower using 1/4- or 1/2-inch rings yields higher transfer coefficients than a countercurrent tower packed

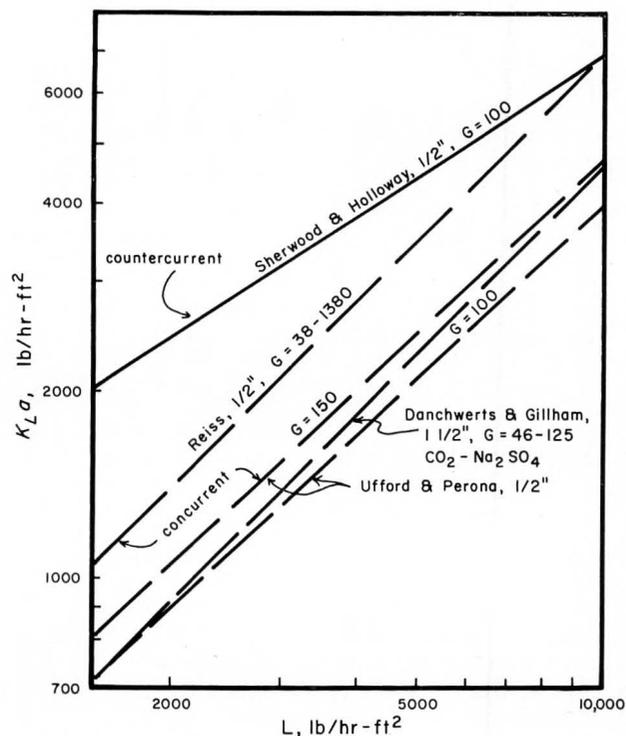


FIGURE 3. Mass transfer coefficients for Raschig rings at higher gas mass velocities, CO₂-air-water except for Danckwerts and Gillham.

with 3/8-inch rings at a gas rate of 58 lb/hr-ft². At first glance, without examination of other parameters, the concurrent tower would obviously be much superior to the countercurrent tower for high flow rates. It must be remembered that this only applies to the CO₂-water system.

Over a range of 3/8- to 1/4-inch Raschig rings in countercurrent flow, Koch, Stutzman, Blum and Hutchings (1949) found that the following correlation fit all their dates within ± 10.1%.

$$k_L a = 0.25 L^{0.96}$$

where L is given in lb-moles/hr-ft² and k_La is given in lb-moles/hr-ft² (lb-moles/ft³). The liquid flow rates were varied from 61.2 to 4140 lb/hr-ft², while the gas rates were varied from 18.75 to 84.3 lb/hr-ft². Thus, the data of Koch *et al* was used as a comparison with Ufford and Perona because the power dependence of L is approximately the same. The Koch *et al* coefficient is 2.0 to 2.5 times larger at the lowest liquid flow rate and 2.1 to 2.17 times larger at the highest (extrapolated) liquid flow rate than the 1/2- or 1/4-inch ring coefficients of Ufford and Perona. Ufford and Perona state that Koch *et al* found little variation of k_La for all sizes of rings. This is not quite true. Koch *et al* found up to a 24% deviation using the 0.96 correlation for 3/8-inch rings, and no deviation for 3/4- and 1-1/4-inch rings, (their Tables 3, 4 and 6). As Koch *et al* explained it, "It may be pointed out that different powers on L could have been used within the experimental error of the data, and it is possible to use an exponent of 0.8 which is the more widely accepted one. However, a careful analysis of the data indicated that an exponent of 0.96 represented the best compromise between average deviation of the data and representation at both extremes of liquid rates."

Reiss (1967) experimented with stacked and dumped 1/2- and 1-inch Raschig rings for oxygen desorption in concurrent flow. He found that his data fit an expression in the form of the Ergun (1952) equation:

$$\delta \left(\frac{g_c \rho D_p^3}{\mu^2} \right) \cdot \left(\frac{\epsilon}{1-\epsilon} \right)^3 = \alpha Re + \beta Re^2$$

where

$$Re = \frac{D_p V \rho}{\mu (1-\epsilon)}$$

The values of α and β are different for each type of packing. Reiss based his mass transfer

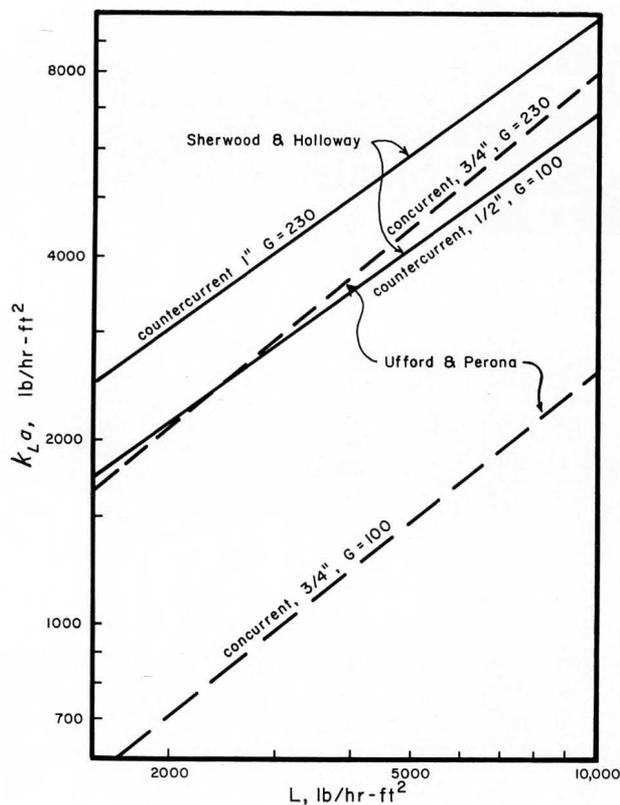


FIGURE 4. Mass transfer coefficients for Berl saddle packings, CO₂-air-water system.

coefficients on an energy dissipation function for the liquid phase:

$$E_l = V_l \left(\frac{\Delta P}{\Delta Z} \right)_{lg}$$

where $(\Delta P/\Delta Z)_{lg}$ is the pressure gradient of the gas-liquid phases combined and V_l is the superficial liquid phase velocity.

Reiss' correlation allows design calculations that are accurate to ± 50%. From representative calculations it can be seen that there is a definite gas flow rate dependence because the frictional pressure gradient, δ, must be calculated for both phases using the Reynolds number for each phase. Gas flow rates ranging from 138 to 1380 lb/hr-ft², and liquid flow rates ranging from 2246 to 22,460 lb/hr-ft² were used. A comparison between the coefficients of Ufford and Perona with those of Reiss at a gas rate of 150 lb/hr-ft² and various liquid rates is shown in Table 2. At the lowest liquid flow rate, the coefficient of Reiss is 1.3 times larger than that of Ufford and Perona for 1/2-inch rings. At the highest liquid flow rate, the Reiss coefficient is 1.47 times larger. Sherwood and Holloway (1939) and Higbie (1935)

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USE OF FLOWTRAN SIMULATION IN EDUCATION

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OVER THE PAST few years, one of the major efforts of the CACHE Committee (Computer Aids to Chemical Engineering, a committee of the National Academy of Engineering) has been the installation and maintenance of FLOWTRAN on a commercial network for use by ChE educators. FLOWTRAN is a large, general-purpose, steady-state simulator of chemical processes with extensive facilities for physical and thermodynamic property data handling and a large library of equipment modules, including cost estimation capability. It was developed by the Monsanto Company for internal use and was offered, for a time, as a commercial service by Monsanto. Currently, FLOWTRAN is available only by outright purchase (at a cost of \$105,000) to commercial users.

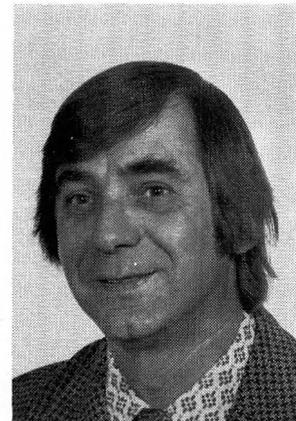
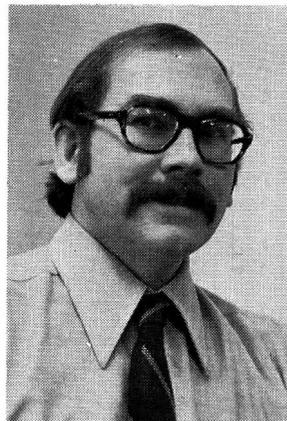
In 1972 the Large Scale Systems and Program Distribution Task Forces of CACHE examined most of the commercially available general-purpose simulators in a search for one that would best serve ChE departments. The decision to concentrate on FLOWTRAN resulted in initial inquiries to Monsanto in 1972. On December 10, 1973 Monsanto agreed to make FLOWTRAN available to universities via a national computer network. Further, Monsanto provided a cash grant to subsidize the installation of the program on a commercial network (United Computing System, Inc.) and the preparation of a text by CACHE to aid users. In addition, Dr. A. C. Pauls of Monsanto was assigned by Monsanto as a consultant to CACHE to assist in the use and promotion of the system.

This paper reports on experiences with FLOWTRAN since its installation for educational use in mid-1974. The authors are co-chairmen of

the FLOWTRAN User's Group, which has been established to aid users and further additional exploitation of this new teaching and research resource.

FLOWTRAN ACCESS

FLOWTRAN IS INSTALLED on a CDC 6600 in Kansas City, headquarters of UCS. There are two ways of accessing the program: by slow-speed terminals (RJE, Remote Job Entry) or by high-speed terminals (RBE, Remote Batch). Slow-speed terminals are such devices as Teletypes or Execuports; there are many high-speed terminals, such as those made by Unitech, Mohawk, and CDC. For the use of slow-speed terminals, UCS provides local phone numbers in



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J. Peter Clark received his B.S. in Chemical Engineering from Notre Dame and his PhD from the University of California, Berkeley. Before joining the faculty at Virginia Tech in 1972 he spent four years in the U.S. Agricultural Research Service. His research interests are food engineering, chemurgy, plant tissue culture, and waste water treatment. He teaches design, simulation and optimization and serves as co-chairman of the FLOWTRAN Users Group.

TABLE 1

FLOWTRAN Consultants by Region

about 90 cities. These are nodes from which data is sent over USC's own lines to the computer, thus saving the user phone charges. High speed users call directly to Kansas City over WATS lines (toll-free 800 numbers). Originally it was felt that most users would only have access to slow speed terminals and so the wide coverage of UCS influenced its choice as a network. In practice, most users have found a high-speed terminal, which is more economical. Details on procedures for using FLOWTRAN from either sort of terminal are provided in a manual [1] written by Dr. R. R. Hughes of Wisconsin, which is given to each user.

User's gain access to FLOWTRAN by signing a three-party contract among CACHE, Monsanto and the user. A potential user should attend one of the Workshops offered by CACHE through AIChE before attempting to use the system. The Workshops are based on the text written by J. D. Seader (Utah, W. D. Seader (Pennsylvania) and A. C. Pauls (Monsanto) with an extensive example by R. R. Hughes (Wisconsin). [2] The text is available from Ulrich's Bookstore in Ann Arbor, Michigan for \$9.95 with discounts available to bookstores. The primary provision of the agreement is that the user will only use FLOWTRAN for teaching and research purposes. After signing, the user receives an account number, password, and as many user IDs (for his students) as he specifies.

To aid and encourage users after training and to promote further use, the FLOWTRAN User's group holds meetings at many AIChE meetings, publishes a newsletter which is sent to all departments, provides consultants and is collecting information (such as problems for class use) for dissemination by CACHE. The consultants and their addresses are listed in Table 1.

EXTENT OF FLOWTRAN USAGE

AS OF JUNE 30, 1974, there were 25 user schools with cumulative billings to that date of \$15,716. Professors from about 50 schools attended two FLOWTRAN workshops (Northwestern in August 1974 and Houston in March 1975). Another workshop was held in Boston in September 1975. The range of billings, as of June 30, 1975, was up to \$2890. Five schools had spent over \$1000 and eight others had spent between \$500 and \$1000. Two other schools have issued purchase orders.

The cost of using FLOWTRAN on the UCS

New England: NJ, PA, MD, DE, NY
Warren D. Seider Department of Chemical Engineering University of Pennsylvania Philadelphia, PA 19174
Southeast: NC, TN, SC, GA, FL, AL, MS
Jude T. Sommerfeld Department of Chemical Engineering Georgia Institute of Technology Atlanta, GA 30332
Mid-Atlantic: VA, WV, OH, KY, MO
J. Peter Clark Department of Chemical Engineering Virginia Polytechnic Institute and State University Blacksburg, VA 24061
Great Lakes: MI, IN, IL
Richard S. H. Mah Department of Chemical Engineering Northwestern University Evanston, IL 60201
Midwest: WI, MN, IA, KS
Richard R. Hughes Department of Chemical Engineering University of Wisconsin Madison, WI 53706
Everything else (West and Southwest)
J. D. (Bob) Seader Department of Chemical Engineering University of Utah Salt Lake City, UT 84112
Consultant to the Consultants
Allen C. Pauls Corporate Engineering Department Monsanto Company St. Louis, MO 63166

network is not excessive. Using Remote Batch Entry on overnight service, costs run from approximately \$2.00 for small jobs to \$7.00 for large jobs. One technique for minimizing cost while the student is learning to use FLOWTRAN is to require "dry runs" (i.e., FLOWTRAN input data on computer coding forms that are checked for errors, but not executed). Students are supplied FLOWTRAN solutions to their "dry runs" for analysis. Only then are they permitted access to the computer.

A problem of "hard" vs. "soft" computer money may exist. Some campuses have an internal budget for computing which involves only paper transfers of funds. Use of FLOWTRAN requires a purchase order to UCS for real or "hard" money. However, this problem is not insurmount-

able. With the advent of external networks, many computing centers are changing to a "real money" system of accounting. Also, there are sources of money for educational purposes, such as teaching innovation grants, on many campuses which can fund activities like using FLOWTRAN. Judging by the volume of usage so far, professors have been creative in persuading their departments to provide the resources necessary to gain access to FLOWTRAN.

HOW IS FLOWTRAN USED?

THERE SEEM TO BE at least four categories of FLOWTRAN use. These are: conventional process design courses, computer-aided design electives, separations courses, and thermodynamics courses. Without a detailed survey, we can only speculate on the distribution of actual usage, but these four categories embrace those we have learned of. It is remarkable that the system is versatile enough to include so many possibilities.

In conventional process design courses, one procedure is to assign cases to groups or individuals who, after training and orientation to FLOWTRAN, use the system to prepare a design report, possibly including an economic evaluation. Many interesting processes can be analyzed using FLOWTRAN with relatively little difficulty. For example, the FLOWTRAN system includes physical property constants for 180 chemical compounds. It also includes 30 modules for simulating equipment items. It is not difficult to add new compounds or new equipment modules, such as special-purpose reactors, as they are needed. FLOWTRAN frees the student from tedious and repetitive calculations, allowing him to explore parametric cases and flow-sheet variations. Obviously, good judgment in evaluating the results must be emphasized since FLOWTRAN, like any computer program, will only do what it is told to do.

A slightly different orientation exists in courses that emphasize computer-aided design, a fairly common elective or extension of the conventional design course. Here the point really is to learn problem formulation (where to tear recycles or how to avoid them) and also come to understand the characteristics and limitations of models and simulators. Another objective, frequently as a research topic, might be how to extend the usefulness of general purpose simulators. Hughes, for example, described the use of FLOWTRAN in optimization in a recent paper. [3]

Finally, FLOWTRAN contains some powerful facilities for the study of complex vapor-liquid, vapor-liquid-liquid, and liquid-liquid separations and correlation of thermodynamic data for pure compounds and nonideal mixtures. These facilities were included to support design efforts and, of course, are valuable there. But they can also stand alone and be exciting adjuncts to graduate courses in these subjects.

FUTURE DEVELOPMENTS

FLOWTRAN USAGE IN universities is off to a good start but clearly has not reached its full potential. Usage under the present arrangement is expected to about double in the next academic year. Beyond that it will grow at a less rapid rate. In the meantime, however, other developments may greatly expand the community of users.

The CACHE Committee, because of its experience with FLOWTRAN, is one of the leaders in the field of academic application of computer networks. A network is an arrangement of computing facilities which exchange resources and data over a communications medium, such as telephone lines or microwave links. UCS is a commercial network with one host (containing FLOWTRAN among many other resources) and many nodes. Soon, there are likely to be one or more multi-host networks connecting educational institutions. In fact, a prototype network involving twenty universities will probably be established within a few years. FLOWTRAN as an example of a large-scale resource for ChE, will probably be installed on this prototype network. One of the consequences will be much lower costs for those fortunate enough to have access to the network. If the prototype is successful, the network will almost surely be expanded to involve many more institutions.

The CACHE Committee, through its Task Forces, is examining other resources that could be provided to ChE departments. Among the possibilities are: process synthesis programs, physical and chemical property data bases, and safety and reliability analysis programs. There are many problems to be solved before another large system can be widely disseminated, including documentation, maintenance, and easy access. However, it is quite likely that ChE educators can anticipate further expansion of their arsenal of computer-based weapons in the next few years. Willing volunteers for the many tasks that must be handled first are urged to make themselves known. □

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1. Hughes, R. R. "CACHE Use of FLOWTRAN on UCS," CACHE, Inc., Cambridge, Mass. 1975.
2. Seader, J. D., W. D. Seider, A. C. Pauls. "FLOWTRAN Simulation—An Introduction," CACHE, Inc., Cambridge, Mass. 1974.
3. Hughes, R. R. "Optimization Methods for Block Simulation," paper presented at VI Interamerican Congress of Chemical Engineering, Caracas, 1975.

WORCESTER POLYTECHNIC INSTITUTE

Continued from page 73.

addition to the Department faculty, Bob Thompson, who is an expert wine maker and bread baker.

The Department had its beginnings in 1922 when the late B. F. Dodge, then a recent PhD from Harvard, was invited to be lecturer in Industrial Chemistry and Chemical Engineering for the senior chemistry students. In 1925 T. K. Sherwood was appointed to the faculty to broaden the ChE curriculum within the chemistry department. In 1940 Ernest Wilson, a chemical engineer, became the chairman of the combined chemistry and ChE department, and until his death in 1958, he built a faculty, laboratory facilities and a strong undergraduate program. Beginning in 1958, Wil Kranich presided over a growing graduate and research program, a new building, and the redirection of the undergraduate program under the WPI Plan. When Kranich became Dean of Graduate Studies, the chairmanship passed in 1975 to Imre Zwiebel. With a strong department faculty and a healthy level of outside support, challenges and opportunities still remain for growth, excellence and unknown new horizons. □

WPI

CHEMICAL ENGINEERING FACULTY

Kohler, J. T.:	Assistant Professor Biomedical and enzyme engineering, biotransport phenomena
Kranich, W. L.:	George C. Gordon Professor and Dean of Graduate Studies Catalysis, process development
Ma, Y. H.:	Associate Professor (Professor as of July 1, 1976) Applied mathematics, simulation, diffusion in porous solids
Meador, J. W.:	Assistant Professor Rheology, heat transfer
Sand, L. B.:	Professor Materials synthesis, molecular sieve catalysts, sorbents, geochemistry
Thompson, R. W.:	Assistant Professor Adsorption phenomena, applied kinetics and chemical reactor behavior, emulsion polymerization kinetics
Wagner, R. E.:	Professor Nuclear technology, transport phenomena, thermodynamics
Weinrich, S. D.:	Leonard P. Kinnicutt Assistant Professor Systems analysis, optimization, process control
Weiss, A. H.:	Professor

Complex reaction kinetics, catalysis, resource recovery

Zwiebel, I.: Professor and Department Head
Adsorption, applied mathematics, reactor design, process design, mass transfer

VISITING RESEARCH FACULTY

1975-76

Aharoni, C.:	Technion—Israel Institute of Technology, Haifa, Israel Catalysis, adsorption
Aiello, R.:	University of Naples, Naples, Italy Molecular sieves
Antoshin, G.:	USSR Academy of Science, Moscow, USSR Catalysis
Guczi, L.:	Institute of Isotopes of the Hungarian Academy of Science, Budapest, Hungary Catalysis

ChE book reviews

PARTICLE SIZE MEASUREMENT

by Terry Allen

Halsted Press, 1975. 454 pages, \$25.95.

Reviewed by Clyde Orr, Georgia Institute of Technology

The author, a Lecturer at the University of Bradford in England, has expanded and partially updated his earlier edition of the same title. Coverage is broader than the title would suggest, encompassing, in addition to the stated subject, treatment of sampling, surface area evaluation, and pore determinations in porous materials. An effort is made to develop the theoretical background of each subject, but much of the treatment consists of technique and procedural reviews. This makes the book valuable for the novice. Others more knowledgeable will recognize the author's bias occasionally creeping into the presentation.

The work consists of 18 chapters the first three of which cover bulk powder sampling from gas streams, and atmospheric sampling. Separate chapters pertain to the treatment of size distributions, to the interaction between particles and fluids in a gravitational field, and to powder dispersion. Remaining chapters are devoted more

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CAN AN ENGINEER BE ACTUALIZED?

A Senior Seminar Course

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Gainesville, Florida 32611

CAN AN ENGINEER be actualized?" This is a question that I have been asking our students in chemical engineering here at the University of Florida for the last three years. No, I haven't gotten a clear and concise answer to the question. You may ask, why even ask it. Why is it important? Particularly, why is it important to me?

The question, I believe, for me as a chemical engineer, has been very important; although I didn't know enough to ask the question when I should have. I worked for a chemical company for seven years after graduating from the University of Michigan in 1951. My first supervisor in that chemical company, a production supervisor, was very much unaware of the characteristics of actualization. As a result, I found myself aching for some honest sharing, and maybe I should say caring feedback concerning my own interaction and productivity in that particular company. I worked with this individual for four years. And really, during that total period of time I never did have any positive, constructive view of my value to the company. If I was doing anything really all right, I never knew it. I now look back at my experience there as a positive one. I learned much, and I think I was a productive engineer. However, I do remember having an aching gut almost every spring when I was working for this company. I believe part of that ache resulted from my lack of knowledge of myself, and, particularly, from the interaction or lack of it with my own supervisor.

After leaving the chemical company to go back to school to obtain a Ph.D., I then joined one of the national laboratories. In that particular organization, much freedom was given to each of the staff members and much of the productivity of that organization resulted from the grass root ideas and the involvement of each staff member,

even though he or she did not have an official title. Unfortunately, I did not realize that my responsibility was to dive in, to let people know where I stood, to let them know what ideas I had and how they should be expedited. Initially, I went back into my little corner, utilizing my new tools obtained in the Ph.D. program, ran the computer, worked with my mathematics, and did not productively contribute to the guidance and sense of direction of the organization. Finally, after about three years of this type of non-involvement, I suddenly became very aware of my potential to the group and to myself. Fortunately, I did turn around and did start to contribute aggressively at every level that was reasonable.

**Can the engineer move
out of Consciousness I and
Consciousness II and still maintain the high level of
productivity and creativity that is necessary
in our very technologically oriented
society of today?**

I've shared with you these two experiences in my own engineering past to give emphasis to my own strong belief that we, as engineers, do need to have some of the characteristics of actualization to be more effective and to enjoy more positively the engineering experience. My own experience in industry has indicated that much of the actualized characteristics are not there among the engineering community. Maybe I should ask why. More important, I should ask, what can we do about increasing the level of actualization, the level of positive interaction that we as engineers can produce in our industrial environment.

CHARACTERISTICS OF ACTUALIZATION

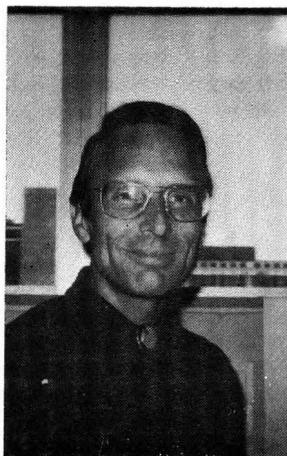
A BRAHAM MASLOW INTRODUCED his ideas of actualization in the mid-fifties, and they have had considerable impact through the

humanistic psychologist upon many of us and also upon industrial management. I feel that there are certain ones of the characteristics of the actualized person that are very meaningful to me, and they are the ones that I would like to emphasize during this presentation. Dr. Maslow discovered in his group of actualized people he studied that they seemed to have certain common characteristics. They seemed to center around words such as honesty, awareness, trust, and openness. I will not try to describe in great detail these terms. Dr. Maslow's books are there to be read, as are others who have utilized his ideas and concepts. But the feeling that I obtained from his works is one of being free, of being very aware of oneself and the human process going on around ourselves, of trusting our own capabilities, and trusting what we do detect in this process, and finally being very open in what we feel and what we would like to express to those about us. The terms "sharing" and "feedback" come to be an important part of this openness, trust, awareness, and honesty. The sharing is sharing of ourselves, of our deep feelings inside. As Jess Lair has said so appropriately in *I Ain't Much, Baby—But I'm All I've Got*, the loving process to him is one of deep sharing. I think that I agree. Also, the actualized person tends to be very much "here and now" oriented. Again, the awareness seems to center on the now. The excitement of the moment stands out. Finally he is process-oriented. The goal, many times, tends to be much less important than the process that heads toward that goal. As a matter of fact, he can brighten the day or brighten the moment in the midst of a very hectic time by making the here and now, the momentary process very delightful and very enjoyable.

ENGINEERS' CHARACTERISTICS

TO ACTUALLY CATEGORIZE the engineer and state his characteristics is a very dangerous process. He obviously is a very talented person, has been very creative in the technological sense, and is a very stable person in the community. I believe the divorce statistics indicate that the engineer has one of the lowest divorce rates among any of the professional groups. He makes a good husband.

However, if you ask the average student on campus about the engineers on campus, we will be viewed as to being quite "square", very dedicated to our books, very non-participative in activities



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on campus, maybe quite unaware of the human process.

In the class seminar I am about to describe, we utilize *Greening of America* by Charles Reich to give us some awareness of the types of people with whom we interact. He has arbitrarily broken down society into three groups, and he calls them Consciousness I, II, and III. In brief, Consciousness I includes those people who are very self-reliant, do not lean on others at all. They feel they can do it alone. The pioneer, who was willing to hack out an open plot of land in a thick forest many miles away from the nearest neighborhood, undoubtedly is very characteristic of Consciousness I.

Consciousness II is the group which has become convinced that the large organization, whether it be large government, or large union, or large industrial corporations, is very necessary in solving all of the problems of society. If there is a problem that exists, the way to solve it is to create another large organization, or another large committee, or another counteracting force to balance those that are existing in the society. The characteristic of the Consciousness II person is that he is a very willing worker, and also a very willing consumer. He is very status-conscious; salary is very important; grades are very important. His

position among the hierarchy is important. He works hard all week mainly to get away on the weekends so that he can go off to his cabin, or the ocean, or to some recreational area that can be totally separated from his work. Many times the work is very unsatisfactory, and his only reason for pursuing his particular profession is to generate money so that the weekends and particularly his vacations can become more meaningful.

Consciousness III is a more difficult group to describe. The group is more human-oriented, tends to care about the human beings around, is very aware of the human process. Goals, particularly

can be rightly asked: can the engineer move out of Consciousness I and Consciousness II and take on some of the characteristics of Consciousness III and still maintain the high level of productivity and creativity that is necessary in our very technologically oriented society of today?

BREAKING OUT OF THE MOLD

IF WE REALLY WANT TO break out of the Consciousness I or II mold, what can we do? The first question is, "Do we really want to break out?" In reading Abraham Maslow's work and also that of Everett Shostrum, I get a thrill and a

In the senior seminar, we concentrate for a while on role playing situations that help in these overall processes. Our students have been criticized before for not handling themselves very well at interviews, and, therefore, we are utilizing the interview process for our role playing situation.

monetary and status goals, are relatively unimportant. Many of the characteristics of Consciousness II have been rejected by Consciousness III. In some respects, the Consciousness III person might be described as being actualized. However, I believe the one-to-one relationship is not totally there.

Charles Reich likes to describe the "hippie" of the mid-sixties as being the characteristic person of Consciousness III—the long hair, the flowing clothes, maybe even the use of drugs. Therefore, by definition, Consciousness III is out of bounds for the "square" engineer—or is he out of bounds for the engineer? I guess the question I like to pursue is, "Are there characteristics of Consciousness III that can be nicely integrated into the intense work regimen of the engineer that can invigorate and enliven his own professional consciousness?"

From my own view, I feel that the engineer generally sits in Consciousness I and II. I have personally worked with engineers who are so independent they will not even say hello in the hall as they walk along. There are others who are very much involved in the work and play schism, as indicated in Consciousness II. Also, many of the engineers become quite subservient to the overall process of industrial involvement of the organization, become very aware of their very tenuous state that they seem perilously to maintain in a given organization. Yes, the question, I think

feeling of, "gee, wouldn't it be nice to have some of the thrill of life that the actualized individual seems to have! His openness, his honesty, his awareness. His feedback and sharing seem to be delightful things to use and participate in." Also, another aspect of the actualized process is that of being dedicated to the growth of the other person, or maybe to a vibrant idea.

This dedication to growth has been expressed very nicely in a book by Milton Mayeroff, the title being *On Caring* which came out in 1971 and is published in Perennial Library in paperback. In that book, he states that the caring process is one of dedicating yourself to the growth of the other person or to an idea or process. To me, this view makes a lot of sense. The growth of one's wife is necessary if the relationship continues to be a vibrant one. Therefore, dedicating some of my efforts to her growth certainly is to me a loving and caring process. In the management field, the best managers, I feel, are those who are dedicated to the growth of the people they manage. They are aware of their needs, and they create an environment which contributes to the growth of these people.

How do we move from one growth level to another? Growth occurs slowly. I am sure that the reading we've done and can do is an important part. We need places to practice, however, the actualized process, even to be aware of what it might entail. My own feeling is group work, group

dynamics, being aware of the dynamics, is a very important part of this growth process. An associate of mine the other day stated that it takes time for one to become what he philosophically states when a change of philosophy has occurred. He indicates that maybe five years are required before a person can really assimilate and be what his philosophy tends to dictate. This is a very saddening realization, because even though I want to be actualized; even though I want to be aware, even though I want to be honest and open, I cannot do it immediately today. I must practice, I must work, I must read, I must utilize the process in everyday life, in maybe artificial situations such as group activity, to be able to make it a part of me.

SENIOR SEMINAR

THE ABOVE STATEMENTS concerning actualization and the possible benefits of trying to be aware of it and the utilization of it as an engineer have been the motivating force behind my presentation and involvement in a senior seminar for our chemical engineering students at the University of Florida. The course meets once a week, is one hour credit, and is totally dedicated at the moment to the study of humanistic processes and the involvement of the engineer in those processes. We utilize *Greening of America* by Reich, *Man, the Manipulator* by Shostrom, *On Caring* by Mayeroff, and *I Ain't Much, Baby—But I'm All I've Got* by Jess Lair as the textbooks in this course. The texts are nowhere near as important, however, as what goes on in the course itself. The group dynamics, the interaction, the sharing, the caring and feedback processes are very important to try, to risk a little, to get the feel of what can and cannot be done.

My own feeling about group work is that it best occurs when it is done in a caring way. The so-called encounter group totally turns me off. I don't like the antagonism and the non-caring that can go on in the so-called encounters. However, the sharing group or the support group can do much to enhance the characteristics of honesty, awareness, trust, and openness we would like to see developed in the members of the group.

In the senior seminar, we concentrate for a while on role playing situations that help in these overall processes. Our students have been criticized before for not handling themselves very well at interviews, and, therefore, we are utilizing

the interview process for our role playing situation. I ask the students to go over to the Placement Center and investigate a given company very thoroughly. A team of two students then will put on an interview for the rest of the group, and actually for themselves. One will be the interviewer and the other the interviewee, and they will go through the total interview as best they envision it. The role playing has many advantages. They do obtain some practice in interviewing. Also, they become aware, with the assistance of the group, of their own participation in that interview, of their own body language, their eye contact, their nervousness or lack of nervousness, their interest or lack of interest in the process. They can be made aware of their manipulative behaviors, if they happen to take on any of the top dog or underdog characteristics as indicated by Shostrom. The interview, as we are all aware, can be very manipulative. It should be one of generating useful information for both participants, and I try to emphasize that the student should make it as non-manipulative as possible. This is a case for openness and being candid, of trying to make the interview useful for learning about the company he is investigating. He should not allow himself to be manipulated, if manipulation starts. All in all, the interviews tend to be quite exciting, and sometimes they are so well done that the students lose themselves in that process and really are totally unaware of the group that is looking on.

The feedback session after the interview also is very worthwhile. We obtain practice in giving feedback, and giving it in a way that can be accepted by the recipient. In many cases, the feedback has to be relatively negative. How can the negative comments be couched in a way that they can be accepted, and then how can the person receiving the feedback accept it in a way so that his self-image is not totally destroyed. We, of course, in the industrial setting have to face this situation time and time again. In actuality, when it comes to employee evaluations particularly, the overall situation may totally be avoided by the supervisor who is not willing to involve himself in sharing and feedback, in honesty, which are necessary to facilitate the evaluation process.

Another aspect of the group dynamics and group interaction that can occur in the seminar is the practice that can be obtained in sharing of one's deepest feelings. This sharing is a very difficult process. However, again, practice does help in making it an important part of our behavior.

RESULTS OF BEING ACTUALIZED

THE STUDENTS IN OUR SENIOR seminar in chemical engineering have not come to any conclusion as to whether the engineer working in our society, and usually for an employer, can be fully actualized, can be a member of Group III, and still be productive. For instance, we discussed recently, the paper Dr. Ray Fahien and I presented at the American Society for Engineering Education Annual Conference in 1973 which was titled "Should Engineering Students Be Taught to Blow the Whistle on Industry?"* In that paper, we discussed the hierarchy of values—extrinsic, systemic, and intrinsic values—and we suggested that, depending upon the type of question being viewed, the engineer might take different actions, both internally in and external to the company. Our group became very aware in the discussion of the paper that to take any action at all requires a great degree of self-confidence in the engineer, a high degree of awareness, and certainly a great feeling of being open and wanting to express honesty. These, of course, are the characteristics of the actualized person. They, also, expressed a great fear in taking the risks that are necessary to be actualized. They felt their jobs might be in jeopardy, and that the Group II values, such as a sumptuous home, a boat, two or three cars, and a house or lot in the country, might be jeopardized if the person actually did behave in a fully actualized way. I believe the group in this discussion the other day was not very hopeful that the engineer, as they viewed themselves and as they viewed other engineers, could actually interact with industry in this manner.

I guess my own view of the situation is much more hopeful. I believe that the risks can be taken, and that the risk can be taken and still productivity can result. As a matter of fact, maybe more useful productivity can result than if the engineer is very passive and a very willing participant of the system, not questioning its sense of direction, both technical and ethical. I may be somewhat naive in my point of view, but I tend to feel that the feelings of Group III consciousness are growing and that they may become a more noticeable part of the large governmental, industrial system

*"Should Engineering Students Be Taught to Blow the Whistle on Industry" was presented by John Biery and Ray Fahien at ASEE 1973 Annual Conference in Ames, Iowa, and was published in the Fall 1975 issue of *CEE*.

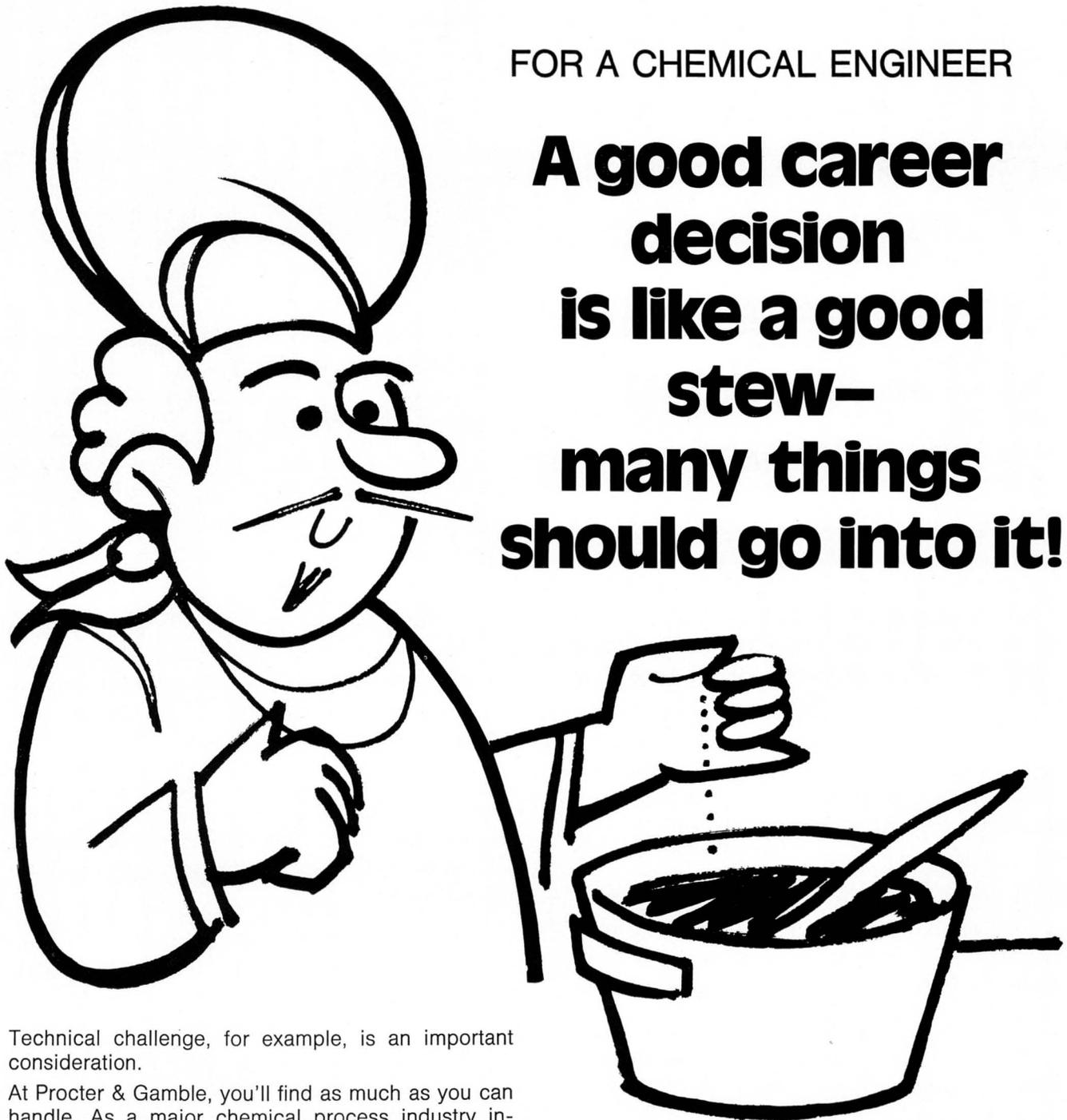
in which we are now involved.

In the discussion that followed the presentation of this paper on "Whistle Blowing" at the Annual Conference in Ames, Iowa, the participants there felt very similarly to the members of my senior group—that the action necessary actually to blow the whistle on industry would seldom occur. However, at least one member of the audience indicated that if a higher percentage of us were willing to risk, then that percentage would tend to grow. So it means if we, as engineers, are to be actualized and are to actually express our feelings and try to influence the sense of direction of an organization, we will have to take the risks pretty much alone. But, if we so do, there is a good chance that others will finally risk with us.

What I am suggesting is that the actualized engineer is a possibility, and that productivity and the excitement from that productivity may well increase if we have more of us who actually have actualized characteristics. The risks are not trivial in speaking out, in being honest, and being aware of our human situation. But my own feeling is that these risks are worth taking, and they make the job itself very exciting.

RESULTS OF THE SEMINAR

WHAT DO I THINK the results of such a seminar as we are conducting in chemical engineering might be? I certainly do not want to delude myself in thinking the students in this class will go out and take the risks necessary to be totally actualized. However, I am sure many of them will now be much more aware of their role in industry and the fact that they do have an obligation to let their views be felt. I do hope that their awareness of their interaction in the company is heightened, and that their ability to speak up, particularly in the technical sense, is increased. Also, they can become better supervisors by being again very aware of the human process about them, aware of the needs of the people they are supervising, and then being able to take again the risks that are necessary to make the human process within their group a vital one. Yes, I do feel our engineers can have many of the characteristics of the actualized individual as postulated by Maslow. And, for those of you who are in the industrial community or even in the academic community, I hope we have the pleasure of interacting more frequently with an actualized engineer. □



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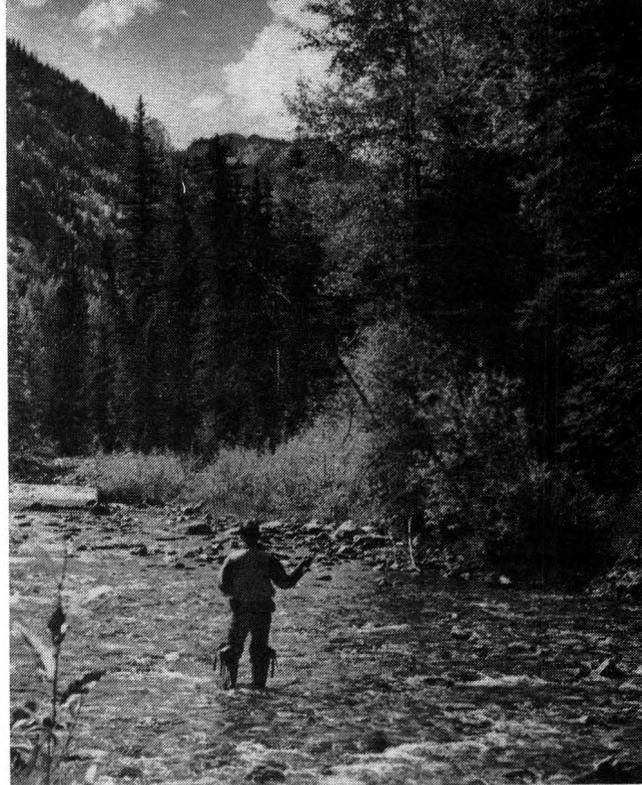
SUMMER SCHOOL IN SNOWMASS

The next Summer School for ChE Faculty will be held in Snowmass, Colorado, during the week of July 31 through August 5, 1977. The Summer School has been held every five years, under the sponsorship of the Chemical Engineering Division of ASEE. The last previous Summer School was held at the University of Colorado in Boulder in 1972.

Snowmass is located just minutes away from Aspen, in a high (8000 ft.) mountain valley, surrounded by 14,000-ft. snow-capped peaks. It is one of the most popular ski resorts in the nation during the winter, and is a secluded but active and attractive alpine resort in the summer. The Summer School has arranged lodging, at quite reasonable prices, in two adjacent inns and nearby condominium facilities. Along with the lodging, Snowmass will provide large-group eating facilities, classrooms and meeting rooms. For off-hours

TABLE 1. Companies providing financial support for 1977 summer school for Chemical Engineering Faculty.

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Stauffer Chemical Company
Union Carbide Corporation
Upjohn Company
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Envirotech Corporation



Snowmass offers many individual and family activities from which to choose. Hiking trails to the mountains start from the front door, and the famous Maroon Bells area of the Rockies is nearby. There are also golf, tennis, riding, raft trips down the Roaring Fork, and 13 swimming pools available to participants. Some families may wish to take advantage of the "Kindeheim," which offers day-time child-care services. Then there is Aspen itself, with interesting shops, old-West Museums and the reknowned summer Music Festival.

Co-Chairmen of the Organizing Committee for the Summer School are C. Judson King and Michael C. Williams of the University of California, Berkeley. They have arranged the program in a Gordon-Conference format, with scheduled sessions in the mornings and evenings and with afternoons free. There will be opportunities for attendees to meet in informal discussion in off-hours, as they may desire. The program is built around a series of one- and two-day workshops, arranged so that there will be six simultaneous workshops at any time. The workshops are arranged by areas of interest, with opportunities for participants to switch between areas during the week if they wish. The theme of the program is "Expanding the Horizons of Chemical Engineering," with six main program areas.

These areas, and their chairmen, are as follows:

- **BIOLOGICAL** (Stanley M. Barnett, U. of Rhode Island) will include sessions on education in bio-technology

fermentation and enzyme engineering, and food processing.

- PROCESSES AND INDUSTRY (T. W. Fraser Russell, U. of Delaware) plans workshops on the economic structure of the chemical industry, process economics and industrial chemistry.
- CHEMICAL REACTIONS (Alexis T. Bell, U. of California, Berkeley) will cover instruction in chemical kinetics, catalysis and subjects related to reactor design and dynamics.
- APPLIED CHEMISTRY (Donald R. Woods, McMaster U.) is considering courses in electro-chemical engineering, metals processing, surface and colloid chemistry, and solid fluid separations.
- TEACHING METHODS (Ernest J. Henley, U. of Houston) will take up motivational techniques and alternatives to the lecture, as well as courses and curricula for non-chemical engineers and a modular course on safety and reliability analysis.
- ADMINISTRATIVE (John W. Prados, U. of Tennessee) tentatively will include sessions on evaluating faculty

workload and performance, as well as faculty recruitment. Other sessions deal with the social and political aspects of engineering decision making, and one or more special topics.

The detailed content of the workshops is still taking form.

Financial support for the Summer School is being donated by a number of industrial companies. At the moment there are 15 participating companies, listed in Table 1. It is anticipated that the number of participating companies will soon reach 20 or more, further reflecting the broad base of funding for the Summer School. The level of financial support is such that it will be possible to give a travel subsidy to attendees from the various universities around the country. Information concerning applications for attendance and available subsidy will be distributed to Chairmen of ChE Departments, probably in late 1976.

HUBBARD: Instruction By the PSI Method

Continued from page 79.

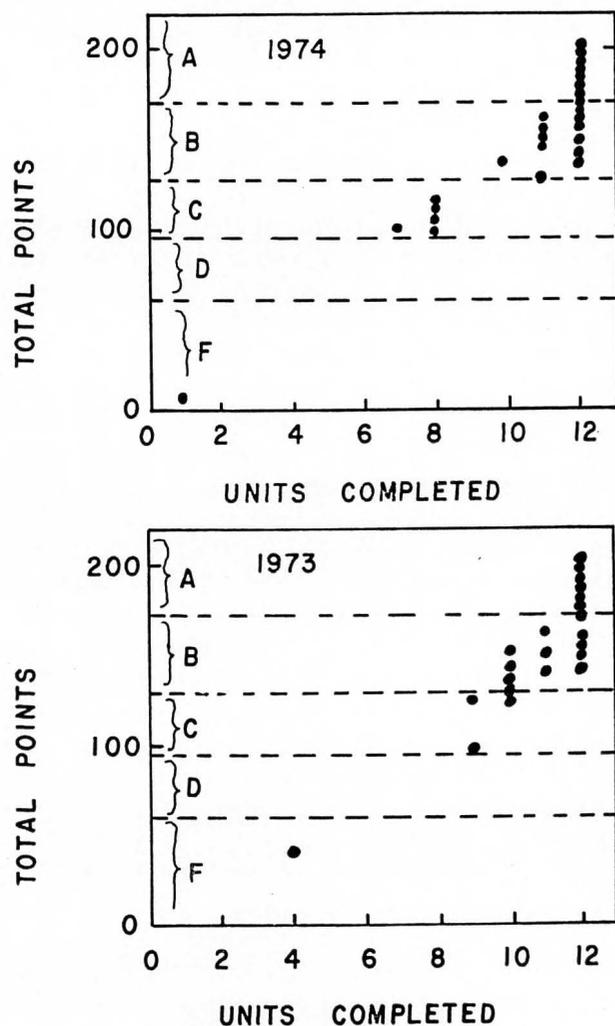


FIGURE 8. Total Score Correlations.

tutor system. They generally feel that supplementary notes could be written more clearly. Eighty-eight percent of the students returning the questionnaire feel that they learn more studying by the PSI method. Fifty-five percent of the students say that they prefer the PSI method to the lecture method. This is a somewhat lower preference than is usually seen for a PSI course. An overwhelming majority of students returning questionnaires usually say they prefer the PSI method. The lower positive response for the process dynamics and control course may be due to its being a required course. When there is a choice of format as in the required dynamics course mentioned above, thirty-three percent of the students usually choose the self-paced method. For the process dynamics and control course, students who prefer a lecture format do not drop out, because there is no choice. If there were a choice, those students would drop out and would not have the opportunity to fill out a questionnaire. The questionnaire data from elective courses may be biased in favor of PSI. □

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suggested the square root dependence of diffusivity for the mass transfer coefficients. If this diffusivity correction is used for the oxygen to carbon dioxide system, the Reiss coefficient is only 1.20 to 1.36 times larger. This shows good agreement over the ranges studied. Reiss found a liquid flow rate power dependence of 0.99 compared to 0.93 for Ufford and Perona. This also shows good experimental agreement.

McIlvroid (1956) also did concurrent flow oxygen desorption studies using dumped 1/4-inch Raschig rings, and 4- and 6-mm glass beads. Gas rates ranged from 400 to 4000 lb/hr-ft², while liquid rates varied from 7080 to 94,350 lb/hr-ft². Two distinct mass transfer mechanisms were found using the glass beads at various gas rates. The mechanism at the lower gas rates was due to a thinning of the liquid film with a corresponding decrease in contact time and increase in k_1a . As the gas rate increased, a more even distribution of the liquid phase with an increase in the effective wetted area available for mass transfer was found. A point was found at which all of the available area was completely wetted. At the higher gas rates, the effect on k_1a was not as great because the film thickness continued to decrease, and/or the higher rates caused higher turbulence. The Raschig rings had only one mechanism present because of the hollow shape. This prevented a completely even distribution of the gas and liquid phases through the packing. Reiss (1967) found that McIlvroid's data fit his correlation well, but from Figure 18 of Reiss, there is either slightly less dependence on the liquid rate or slightly higher dependence on the gas rate.

Danckwerts and Gillham (1966) experimented with 1-1/2-inch Raschig rings in concurrent flow. They absorbed CO₂ into 0.53M sodium sulphate solutions. Gas rates ranged from 46.4 to 125.4 lb/hr-ft², while liquid rates varied from 2210 to 11,200 lb/hr-ft². Their mass transfer coefficient is compared to that of Ufford and Perona in Table 2 at a gas rate of 100 lb/hr-ft² and various liquid rates. Although the coefficients are equal at the lowest liquid flow rate, the comparison is between 1/2- and 1-1/2-inch Raschig rings. The power dependence of the liquid flow rates are quite close though, 0.93 for Ufford and Perona and 1.0 for Danckwerts and Gillham. Upon closer examination, using the correc-

tion for diffusivity in the form $\sqrt{D_{ss}}/\sqrt{D_w}$, the coefficients from Danckwerts and Gillham are 6.45 and 7.35 times larger than those of Ufford and Perona. It must be remembered that the packing is 1/2- and 1-1/2-inch in size. The diffusivities, D_{ss} and D_w , represent CO₂ in sodium sulphate and water, respectively.

Sherwood and Holloway (1939) also experimented with 1/2- and 1-inch Berl saddles at gas flow rates of 100 and 230 lb/hr-ft² in countercurrent flow, respectively. Comparison of their coefficients with those of Ufford and Perona for these gas rates are shown in Table 2. For the 1/2-inch saddles of Sherwood and Holloway compared to the 3/4-inch saddles of Ufford and Perona, the 1/2-inch saddle coefficients are 3.16 and 2.66 times larger at the lowest and highest liquid flow rates, respectively. The 1-inch saddles' coefficients are 1.48 and 1.23 times larger at the lowest and highest flow rates, respectively. The power dependence of the liquid flow rate for countercurrent flow is 0.72 and 0.82 for concurrent flow. There were not enough gas flow variations done to determine gas rate dependence.

Ufford and Perona state that their coefficients are smaller as packing depth increases. They imply this is what is found experimentally. From Equation (15) it can be seen that this is a direct result of how they calculate their results. Since the packing height, Z , is in the denominator, any increase will correspondingly decrease the mass transfer coefficient. The \ln term will probably change too, but not as severely as the inverse of the packing height. Danckwerts and Gillham (1966) do not suggest that the effect is not significant. From their Figure 15 they show experimental data up to 7 column diameters for two different flow rates that the transfer coefficient is independent of packing height. Their coefficients are reported in cm³/sec and are, therefore, not on a per volume of column basis. Wen *et al* (1963) found that, indeed, with a deeper bed k_ga will decrease. From their Figure 18, the number of transfer units, N_{OG} , is a linearly decreasing function over a range of packing heights of from 1 to 3.6 column diameters. But, if k_ga is plotted on log-log paper as a function of Z , above approximately 2 column diameters the negative slope begins to increase dramatically indicating a large effect. Although these results are in-

dependent of all variables except packing height, their coefficients still contain a height dependence. This is because their coefficients are based on a per volume of column basis, and any comparisons should be made on a per area of column basis independent of height. This phenomenon was explained and observed as channeling.

Ufford and Perona stated that coefficients measured with a height of 8.5 column diameters were much lower by factors of 3 to 4 compared with those measured with a height of 2.5 diameters at the lower liquid rates. They find this surprising. However, they base their coefficients on a per volume of column basis. This means that the height of packing is still a factor in the coefficient. If they based the coefficients on a per area of column basis and then compared the coefficients at the lower rates, it would be apparent that the coefficients were about the same. A packed height of 8.5 diameters compared to 2.5 diameters is greater by a factor of 3.4, which falls almost halfway between their lower values of 3 to 4. At the higher liquid rates, the factor was about 1.5. Basing their coefficients on area again, this shows the 8.5 diameter coefficients to be about 2 times larger than the 2.5 diameter ones at the higher rates. This is more interesting because they would then have larger coefficients in deeper packed beds.

Ufford and Perona cited Porter and Templeman (1968) as having verified that the proportion of liquid flowing down the wall decreased as the ratio of the column diameter to the packing particle diameter increased and as the liquid rate increased. They then state that the Berl saddles, according to Porter and Templeman, should be 2 to 3 times larger than the rings. Actually, they should be 1.5 to 3 times larger. As Ufford and Perona stated, Porter and Templeman did not employ a countercurrent or concurrent flow, but a stagnant gas phase. There was, therefore, a considerable lack of turbulence effect on their conclusion. This was, apparently unknowingly, indirectly concluded by Ufford and Perona, who stated, "Hence wall flow alone does not appear to explain this effect, . . .".

CRITICAL SUMMARY

THE RESULTS OF the above workers appear consistent in concurrent flow, and in comparison with countercurrent flow with respect to the values of the transfer coefficients. As generally expected, countercurrent coefficients were as much

as 4 times more than the corresponding concurrent coefficients. The coefficients investigated covered ranges of liquid rates up to about 66,100 lb/hr-ft², and gas rates from 43 to 230 lb/hr-ft². For the CO₂-air-water system, the Ufford and Perona correlation for 1/4- and 1/2-inch Raschig rings, and 3/4-inch Berl saddles in the form of $k_L a = CL^r G^s$ is an acceptable relation for design use in its proper flowrate regime. It has been stated (Ufford and Perona) that recent interest and development in the field of gas-liquid reactions in packed beds has stimulated concurrent flow mass transfer research. We do not feel that the CO₂-air-water system is typically common in industry or unique. From a literature survey, it is apparent that the system seems a bit overworked. It would have been more pertinent and informative for our comparison if research had been reported on such systems as H₂S-water absorption, CS₂ scrubbing, or NH₃ absorption. From our survey of the literature, NH₃ absorption would have been more straightforward as an example of a simultaneous absorption and chemical reaction system.

It should be noted that the packings used in the various work reported above by no means cover the sizes and types of packing currently available and used in the chemical process industry. As such, it is difficult to arrive at concrete relations showing the mass transfer coefficients dependence on liquid flow rate and gas flow rate. In general, it can be seen that since the liquid rate dependence is non-linear, there must be a gas-liquid rate interdependence. Ufford and Perona appear to be the first to present gas rate dependency work.

We feel that packed column mass transfer coefficients would be more representative and easier to interpret with respect to packing height if they are reported as being independent of packing weight. Ufford and Perona drew certain conclusions about packing height effects that were shaded by coefficient dependence on packing height. They also made comparisons with other papers that were supposed to be general in nature, but the other papers were specific about what they covered and, therefore, did not allow generalities to be drawn.

A more general concurrent mass transfer coefficient relation must await further work using a wide variety of present day packings and different systems from both simple gas absorption and simultaneous absorption and chemical reaction situations. □

NOMENCLATURE

a	Local interfacial area per unit volume of column, ft ² .
a _o	Packing surface area per unit volume, ft ⁻¹ .
D	Diffusivity, ft ² /sec.
D _p	Equivalent spherical particle diameter, $D_p = 6(1-\epsilon)/a_o$, ft.
E	Energy dissipation per unit volume, lb _f -ft/ft ³ -sec.
G	Gas flow rate per column cross-sectional area, lb/hr-ft ² .
g _c	Conversion constant, 32.2 lb _m -ft/lb _f -sec ² .
H	Henry's Law constant, pressure units.
H _{OL}	Overall height of a mass transfer unit based on the liquid phase, ft. or in.
K	Overall mass transfer coefficient, lb/hr-ft ² .
k	Mass transfer coefficient based on film driving force, lb/hr-ft ² .
L	Liquid flow rate per column cross-sectional area, lb/hr-ft ² .
N	Rate of transport of gas into liquid phase per unit area of contact, lb/hr-ft ² .
N _{OL}	Overall number of mass transfer units based on the liquid phase.
P	Pressure, pressure units.
Re	Reynolds number, $D_p V \rho / \mu (1-\epsilon)$.
S	Column cross-sectional area, ft ² .
V	Superficial velocity, ft/sec.
x	Liquid-phase mole fraction, moles solute/moles liquid.
y	Gas-phase mole fraction, moles solute/moles gas.
Z	Packed column height, ft. or in.
α	Ergun constant used by Reiss (1967).
β	Ergun constant used by Reiss (1967).
δ	Frictional pressure gradient, p.s.i./ft.
ε	Packing void fraction used by Reiss (1967).
μ	Fluid viscosity, lb/hr-ft.
ρ	Fluid density, lb/ft ³ .

SUBSCRIPTS

e	Based on equilibrium.
G	Based on the gas phase.

g	Based on the gas phase.
i	Based on interfacial contact.
L	Based on the liquid phase.
l	Based on the liquid phase.
lg	Based on the gas-liquid phases combined.
x	Based on the liquid phase.
y	Based on the gas phase.
1	Entrance to the packing.
2	Exit from the packing.

SUPERSCRIPT

*	Based on the liquid phase in equilibrium with the bulk gas phase.
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BOOKS: Continued from page 93.

specifically to measurement methods such as those involving sieving, sedimentation (both gravitational and centrifugal), radiation scattering, electrical sensing, permeametry, adsorption, and the like.

The book suffers the common failing of many today because of delay between preparation and publication; few references are latter than 1972. Nevertheless, it alone is nearly current in the field; earlier works are severely outdated. □

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