

CHE

chemical engineering education

VOLUME XVIII

NUMBER 1

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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION



Richard C. Alkire
of Illinois

New Adsorption Methods
WANKAT

\$12 For a Dozen Experiments in CRE
GUO-TAI, SHAU-DRANG

The Process Design Course at Pennsylvania
SEIDER

Modular Instruction Under Restricted Conditions
UTOMO, RUIJTER

Introducing the Regulatory Process into the ChE Curriculum
KING, CHAWLA

Problem: Setting the Pressure at Which to Conduct a Distillation
BARDUHN

Computer Programs for Equipment Cost Evaluation and Economic Evaluation
KURI, CORRIPIO

CHE AT NORTHWESTERN

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The Technological Institute, home of the Department of Chemical Engineering.

ChE department

NORTHWESTERN UNIVERSITY

... THE NORTHWESTERN PHILOSOPHY

JOHN C. SLATTERY
Northwestern University
Evanston, IL 60201

IF YOU READ NO further than this first paragraph, I would like you to leave with the impression that we take pride in our teaching, that we strive to be on the forefront in our research, and that we are committed to meaningful contact with our students. Those priorities provide the guiding philosophy for the department.

This philosophy has been tested by time. This year marks the 40th anniversary of the first class graduating in chemical engineering from the Technological Institute. We awarded our first master's degree in 1945 and our first PhD in 1948.

Our department now includes 18 faculty, 250 undergraduate and 100 graduate students, six visiting scholars, and three postdoctoral fellows. Since modern chemical engineering research is increasingly interdisciplinary in nature, a number of the faculty hold joint appointments with other

As we have become convinced of the synergism, we have chosen to emphasize several broad areas of research rather than 18 individual activities.

departments: biomedical engineering, chemistry, materials science and engineering, mechanical and nuclear engineering, and neurobiology/physiology.

No scale for the comparison of chemical engineering graduate programs exists. It is clear that, while top departments all offer excellent faculty and facilities, there are differences in educational philosophy and in the research interests of their faculties. Our department strives to maintain a balanced commitment to teaching and research. The training of graduate and undergraduate students is taken seriously by all of us.

The prerequisites for admission to graduate work include a bachelor's degree in chemical engineering from a university or college of recognized standing. Graduates of a curriculum in science or in other fields of engineering whose programs

have included sufficient courses in chemistry, mathematics, and physics will also be accepted for graduate work in chemical engineering. However, they may be required to take selected undergraduate courses without credit, in addition to the normal graduate program.

An individual plan of study is arranged for each student after consultation between the student, his or her adviser, and the graduate committee of the department. Every effort is made to design a program covering the fundamentals of modern chemical engineering science and technology while allowing for individual specialization in particular fields of interest.

For the MS degree, we require a minimum of nine (quarter) courses. Research and the preparation of an acceptable thesis may be an alternative to three extra courses.

For the PhD, a minimum of 18 (quarter) courses are required beyond the BS degree or nine (quarter) courses beyond the MS. Students are guided towards this program based on their classroom performances. The formal qualifying exam is oral and focused on the research topic proposed for the thesis. We have no language requirements.

As we have become convinced of the synergism, we have chosen to emphasize several broad areas of research rather than 18 individual activities. In the descriptions that follow, observe that we have encouraged for the same reason interactions between faculty which cross department boundaries. The single paragraphs devoted to individual faculty are meant to give an impression of their activities rather than to summarize their multifaceted research programs.

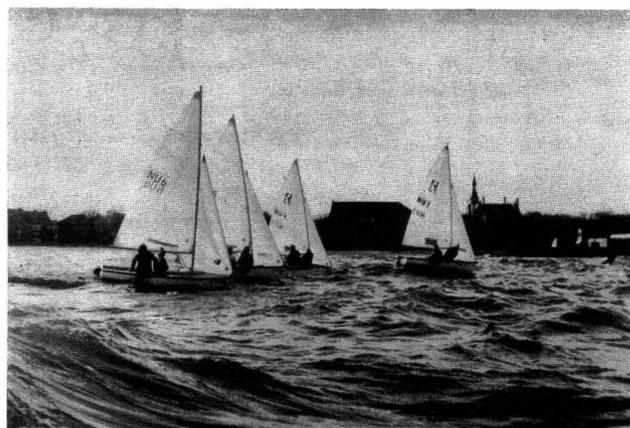
RESEARCH

Chemical Reaction Engineering. The largest single area is chemical reaction engineering: kinetics, catalysis, chemical reactor design, and combustion. There are five faculty active in this area: John B. Butt, Joshua S. Dranoff, Harold H. Kung (who has a joint appointment with chemistry), Chung K. Law (who has a joint appointment with mechanical and nuclear engineering), and Wolfgang M. H. Sachtler (who has a joint appointment with chemistry). This group features extraordinary interactions with faculty in materials science and engineering, chemistry, and physics through the Catalysis Research Center, which will soon have its own building adjacent to the Technological Institute.

John Butt's work in catalysis has been largely

in the area of supported metal catalysts. His group's current research is devoted to the study of hydrogenolysis and hydrogenation reactions on supported Pt group metals and to synthesis reactions on supported iron alloys. Particular emphasis is given to the relationship between the morphology of the supported metal crystallites and their activity and selectivity properties. More generally, John Butt is concerned with the interrelation between catalyst deactivation and chemical process dynamics.

The work of Josh Dranoff and his students in photochemical reaction engineering has previously involved gas and liquid phase photochlorination reactions as well as solution photopolymerization.



A practice race in view of the campus.

Current emphasis is focused on the study of novel photoreactor designs in which the photoinitiation and subsequent thermal reaction steps common to many photoreactions of interest are carried out in spatially segregated zones.

Harold Kung is pursuing the reasons for high selectivities in oxide catalysis. Using modern surface science and catalyst characterization techniques, his group has prepared and characterized both model single crystal oxide catalysts that have high concentrations of a particular type of surface defect, such as anion or cation vacancies, as well as microcrystalline oxide catalysts smaller than 10 nm that possess unusually high selectivities.

A viable approach to enhance combustion efficiency and reduce pollutant formation is through lean combustion. Since lean mixtures are hard to ignite and easy to extinguish, the use of heterogeneous catalysts can significantly extend the lower flammability limits of these mixtures. Ed

Law's group is working to identify the dominant catalytic mechanisms and to determine the associated overall kinetic constants for hydrocarbon/air mixtures flowing over different catalysts.

Wolfgang Sachtler and Harold Kung are studying stereospecific catalysts with the objective of understanding the relationship between the geometry of the active site and catalytic selectivity. On the basis of Wolfgang Sachtler's previous work, it has been proposed that many such reactions involve a dual site mechanism. Their research is aimed towards checking this model and evaluating the prospects of dual site hydrogenation catalysts in general.

Interfacial and Multiphase Transport Phenomena. We have three faculty working in the general area of interfacial and multiphase trans-

. . . we take pride in our teaching, . . . we strive to be on the forefront in our research, and . . . we are committed to meaningful contact with our students. Those priorities provide the guiding philosophy for the department.

port phenomena: S. George Bankoff (who has a joint appointment with mechanical and nuclear engineering), Gregory Ryskin, and me. All three of us find complementary interests in the activities of Stephen H. Davis (who has joint appointments in engineering science and applied mathematics and in mechanical and nuclear engineering). We are involved in such diverse activities as dynamic interfacial phenomena, coalescence, two-phase flows with heat transfer, flows in porous media, flows of suspensions, and structural models for the stress-deformation behavior of polymer solutions.

George Bankoff has been directing a broad program of experimental and theoretical studies on two-phase flow and heat transfer. His particular motivation has been problems associated with nuclear reactor accidents. Rather than studying these complicated problems directly, he and his students have chosen to examine more fundamental problems that can shed light on particular aspects of the overall process.

Gregory Ryskin's current research interests focus on the numerical solution of fluid mechanics problems. He is considering both flows with free boundaries as well as the motions of polymer solutions, the stress-deformation behavior of which is determined by the local microstructure.

My students and I have directed our attention

to a series of fundamental problems concerned with dynamic interfacial behavior and multiphase flows arising in the context of oil production. For example, we have been investigating the influence of the interfacial viscosities upon displacement and the stability of displacement of residual oil from old oil fields.

Polymer Science. Our three faculty whose primary interests are in the area of polymers have joint appointments with materials science and engineering: Stephen H. Carr, Buckley Crist Jr., and John M. Torkelson.

Plastic films that possess either permanent electrical polarizations or electrical conductivity are currently being used as the active elements in such devices as microphones, infrared detectors or batteries. Steve Carr and some of his students

are seeking to understand the origins of the persistent polarization that can be established in some polymer solids. They are studying other polymers that are electronic conductors and act as organic metals.

Using model crystallizable hydrogenated polybutadiene (HPB), Buck Crist's group is making significant advances in understanding the important effects of molecular weight, molecular weight distribution, short chain branching and long chain branching on the structure and properties of semicrystalline polymers. These studies utilize light scattering, x-ray scattering and diffraction, small-angle neutron scattering, calorimetry and density measurements on HPB having extremely well-defined molecular microstructures.

The utility of photophysics in studying macromolecular diffusion-controlled reactions has been demonstrated by studies of intermolecular reactions between labelled polystyrene chains as well as by studies of intramolecular cyclization dynamics of a single polystyrene chain. By a combination of carefully selected fluorescence and phosphorescence studies, John Torkelson is investigating the Rouse dynamics of polymer chains.

Process Engineering. The area of computer-aided process planning, design, analysis, and

control is the interest of Richard S .H. Mah and William F. Stevens.

The research of Dick Mah and his students is directed towards the development of comprehensive theories and techniques for operating processes. One focus of their research is their work on process data reconciliation and rectification, which has already led to new techniques of gross error detection and identification, a rigorous theory of observability and redundancy, and efficient variable and measurement classification algorithms. Another thrust is in the design and scheduling of batch chemical processes.

Process optimization and process control are beginning to depend significantly upon the utilization of equipment and procedures for "real-time" computing. Bill Stevens' current research activities emphasize the development of programs and procedures for the implementation of various "real-time" applications utilizing minicomputers and microcomputers.

Separation Processes. There is currently a developing interest in the department in separation processes.

Josh Dranoff has had a long-term interest in separations based on sorption in zeolites and similar adsorbents. Currently his students are investigating the kinetics of sorption of binary gas mixtures by zeolite adsorbents using a differential bed-chromatographic type apparatus.

Dick Mah's group has proposed and is investigating a new class of distillation schemes designed to enhance overall thermal efficiency. This is accomplished through heat exchange between the rectifying and stripping sections of a distillation apparatus in what is known as secondary reflux and vaporization (SRV) distillation.

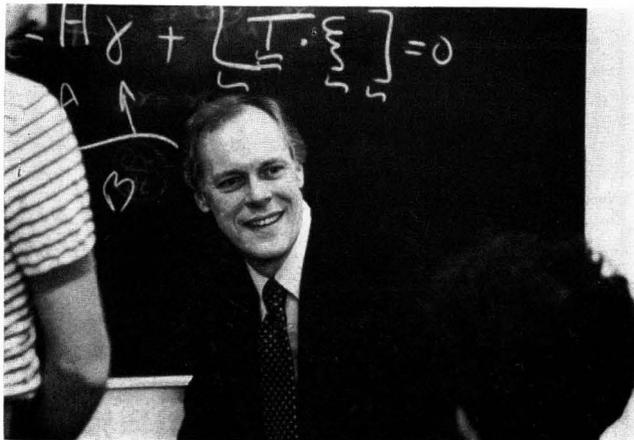
George Thodos and his students are studying the removal of SO₂ from flue gases using regenerable sorbents such as Nahcolite (NaHCO₃), which may offer the possibility of closed loop systems for clean-up of power station stack gases. Separately, he is testing supercritical extraction as a separation tool.

Individual Activities. Naturally, not all of the research in the department is done in the context of group activities.

Thomas K. Goldstick (who has joint appointments with biomedical engineering and neurobiology/physiology) is well known for his long-term interests in biomedical engineering. His

current research centers around the dynamics of oxygen transport in the retina of the eye.

Studies of vapor-liquid equilibria and critical state phenomena continue to occupy the interests of George Thodos and some of his students, while



Chairman John Slattery in an informal discussion with students.

with another group he extends his investigation of solar energy collection and storage.

FUTURE DIRECTIONS

Chemical engineering is an evolving discipline, the one continuous thread being that we are all concerned with applications of chemistry, broadly interpreted. The emphasis given to particular areas of research shifts as the needs of society change, the current faculty matures in its outlook, and we add new faculty.

Looking to the future, we are anxious to expand our activities in the area of computer-aided process planning, design, analysis, and control, when we are presented with the right opportunity. Both the students and faculty agree that this will be a field of increasing importance to the profession.

We would also like to move into biochemical technology. This is not only an area of considerable promise, but also it is one in which, by our judgment, the primary impact of chemical engineers is still developing.

But as we continue to look in new directions, basic priorities will remain unchanged: our pride in our teaching, our eagerness to be on the forefront in our research, and our commitment to meaningful contact with our students. □

Richard C. Alkire

of Illinois

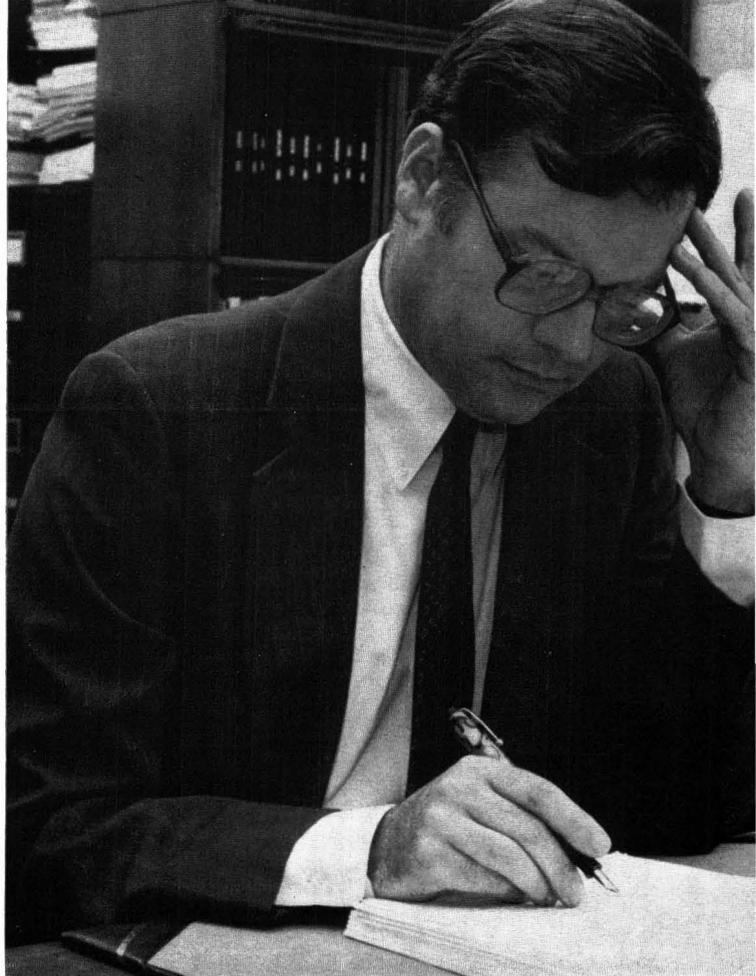
Prepared by his
ILLINOIS COLLEAGUES
University of Illinois
Urbana, IL 61801

TO HIS PROFESSIONAL colleagues, Dick Alkire is known as an electrochemical engineer, to his students as an outstanding teacher and to others through many different perspectives, especially music.

Though he now lives in the heartland of Illinois, Dick grew up in Easton, Pennsylvania, where he graduated from Lafayette College in 1963. For two years of his time at Lafayette, he was tutored on the subject of electrochemical corrosion by Zbigniew Jastrzebski. Traveling to the other coast, Dick attended the University of California at Berkeley to continue the study of electrochemical engineering. Working under the direction of Charles Tobias and Edward Grens, he carried out graduate research on transport processes in porous electrodes. Just to keep things in balance, he enrolled in a piano performance class where he met his future bride, Betty. They left Berkeley in 1968 to spend a post-doctoral year in Göttingen, at the Max Planck Institut für physikalische Chemie, where he studied thermodynamics of solid-state galvanic cells under the late Carl Wagner. A year later, Dick brought his young family back to the United States and took up a post as assistant professor at the University of Illinois. Promotion to associate professor came in 1975, and to full professor in 1977.

... it is Dick's philosophy that "you can't teach research creativity by telling everyone what to do." He gives students a great deal of independence in the pursuit of their thesis research ...

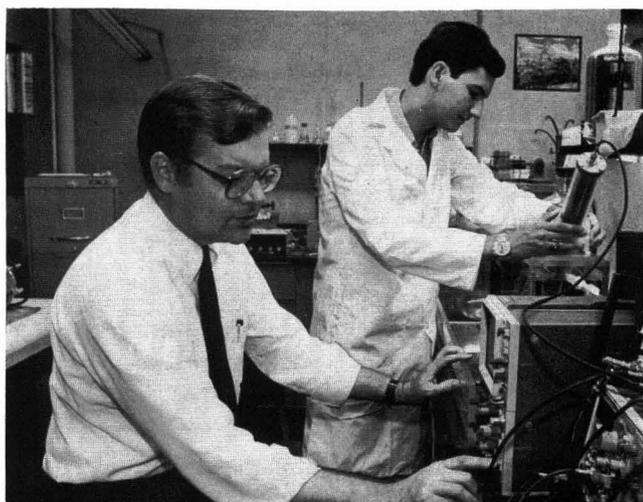
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During these early years, Dick was deeply influenced by his mentors Jastrzebski, Tobias, Grens and Wagner. Under Tobias he had experienced the excitement of a research group that moved steadily into uncharted waters, and with Carl Wagner had had long discussions on how to break open new problems. As a consequence, he embarked on a program of electrochemical engineering research, at Illinois, which continues to this day. At the time, however, the electrochemical field was not common to chemical engineers and it was John Quinn and Roger Schmitz who gave him strong encouragement to maintain his direction.

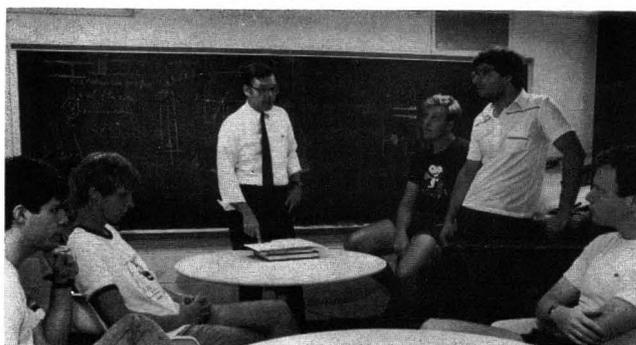
With these perspectives, Dick worked resolutely to broaden his capabilities and interests. He has emphasized application of potential distribution principles to complex electrochemical problems which involve coupled mass transport, ohmic resistance, and interfacial processes. Concentrating at first on electrodeposition, his work for over a decade in that area earned him, in 1983, the Research Award of The Electrodeposition Division of The Electrochemical Society. Also in the early seventies, he returned to corrosion problems where transport phenomena in the solution phase played a critical but unexplored role. Based on his Ph.D. dissertation on crevice corrosion, Dick's student,

David Siitari, was awarded the Young Author's Prize for the best paper in the 1982 Journal of the Electrochemical Society. During a sabbatical leave at Cal Tech in 1976, Dick formulated a new program in electro-organic synthesis, and introduced rigorous chemical engineering concepts to electro-organic reactor design and scale-up. These programs subsequently led to interactions with Robert Sani, at the University of Colorado, in finite element calculations of electrode shape evolution; with Mark Stadtherr, at Illinois, on electrolytic process simulation and optimization; and with Theodore Beck, of the Electrochemical Technology Corp. in Seattle, on corrosion. In 1983, Dick again used his sabbatical leave, this time at the University of Washington in Seattle, to develop a research program in plasma reactor design, where potential field and convective diffusion phenomena play a critical role.



Working with Steve Perusich, Dick investigates transport processes during corrosion. Here, they use focused ultrasound to trigger breakdown of protective surface films, and then study film repair in the presence of fluid flow.

A consequence of these broad and continuing interests is that Dick's research program is by now very large. Last Fall his group included twenty graduate students and a half dozen undergraduate laboratory assistants. Of necessity, a group of such size demands a meticulous management of time and resources. Dick is quick to point out that a major factor in this regard is the excellent reputation with which Illinois attracts truly outstanding graduate students. In addition, it is Dick's philosophy that, "you can't teach research creativity by telling everyone what to do." He



Dick supervises four seminars a week for his graduate students. Shown here (l. to r.) are Steve Lott, Mark Greenlaw, Dick, Bob Schroeder, Demetre Economou, and Kurt Hebert.

gives students a great deal of independence in the pursuit of their thesis research, but demands high standards of commitment, knowledge of the literature, and developing intuitive prowess for linking mathematics to the physical world. One of Dick's former research students observes that "he instills by personal example a deep commitment for achieving a high level of innovation and technical excellence." Another former student notes, "The advice Dick gave me in graduate school in all areas, technical and non-technical, has helped me immensely in my professional career."

To a significant extent, Dick's early years in music have shaped his character and attitudes. Dick and his brother Ed grew up in a family music business where performing came at a young age at the encouragement of Dad, the pro, and Mom, the supporter. Dad, Ed and Dick started playing professionally when Dick was twelve; by the time he was sixteen, they had performed throughout the East and had cut numerous records. Meanwhile, back at the family studio, Dick taught piano, guitar, bass, and vibes, helped run the wholesale and retail businesses, and did much of the art work for Dad's teaching publications. He turned down a four-year organ scholarship to attend Lafayette College to study chemical engineering, but nevertheless performed on over three hundred occasions in the college touring choir, in a barbershop quartet, in a jazz group, and as a solo pianist at weddings and receptions.

The time and energies invested in public performance, in music teaching, and in business-related affairs paid invaluable dividends for Dick's management of his massive research effort today. By the way, his brother is also a chemical engineer with Air Products & Chemicals. Ed is

... no matter how hectic the day ... Dick will always give a student his total attention. His efforts were rewarded in 1982 with the Teaching Excellence Award of the School of Chemical Sciences at Illinois.

Manager of Technical Affairs for the Industrial Gas Division and has responsibility for safety and operating procedures, process engineering, quality assurance, engineering standards, and environmental compliance.

Dick takes it as a given fact that competence in research both requires and demands excellence in the teaching classroom. With a repertoire of a dozen lecture courses, he takes special pleasure in teaching the subjects and in dealing with students on a personal basis. Thinking back on his own training, he recalls that "I have been extremely fortunate to have had teachers who took a personal interest in me and who inspired me to standards which were beyond my awareness at the time. Sometimes those feelings of inspiration came from only brief moments in their presence when I felt that their entire energies were directed toward giving me an appreciation of the subject matter." As a result, no matter how hectic the day, in the classroom or in his office, Dick will always give a student his total attention. His efforts were rewarded in 1982 with the Teaching Excellence Award of the School of Chemical Sciences at Illinois.

Active in professional pursuits, Dick is the youngest Vice President in the history of the 82-year old Electrochemical Society, and will succeed to the presidency in 1985. He is also a divisional editor of the Society's journal. In the AIChE, he founded a group in 1974 for programming symposia in electrochemical engineering, and has also served as chairman of the Heat Transfer and Energy Conversion Division of the Institute. To quote one of Dick's colleagues, he applies "the same enthusiasm, integrity, and competence to Society affairs as he has to his own students and research."

These experiences, along with extensive consulting activity, serve as critical elements in the continual upgrading of teaching and research. With this activity, he has averaged an off-campus seminar every two weeks during the past four years. As one of his colleagues notes, "A hallmark of his work is his ability to translate results of complex calculations into a form easily understandable to practical users in the field." Like the

family music business, Dick's life represents a total commitment to advancing the electrochemical engineering field so that others will be encouraged to follow.

One activity has brought him a special sense of satisfaction. Emeritus Professor Sherlock Swann, Jr. had been at Illinois since 1927 and had, for 45 of those years, meticulously compiled an exhaustively detailed bibliography of the electro-organic synthesis literature, beginning with the first known paper in 1801. Their friendship had begun, understandably, with a mutual love of music which found Dick spending evenings at Sherlock's home listening to old 78-rpm recordings of the masters. Through this musical bond of



Dick's students often spring surprise parties to bid an affectionate adieu to a graduating member of the gang.

shared trust, Sherlock slowly revealed his incredible bibliography. Dick eventually raised over \$90,000 to support a meticulous effort at indexing and publishing the collection through The Electrochemical Society. The result was deeply satisfying to Professor Swann, who passed away in 1983 after having seen an important part of his life's work brought to fruition.

Music continues to be the center of Dick's outside interests. It seemed ironic at the time that, within a few months of deciding on a college career in chemical engineering, his parents' music business took an upswing and they presented him with a Baldwin grand piano. During the years since, his main hobby has been keeping up a sound technique and broadening his knowledge of the literature. A few years ago, Dick built a two-manual harpsichord to gain access to four more centuries of keyboard literature. His daughters, now 14 and 16, play violin and cello and, in addition, are studying string quartets under Gabriel

Magyar, master cellist for 16 years with the Hungarian String Quartet. Meanwhile Betty, the Berkeley music major, continues the family tradition by operating her own music studio.

In summary, Dick has made a significant contribution by identifying electrochemical phenomena where chemical engineering concepts find welcome application. He has helped unify diverse electrochemical subfields so that intercommunication between them has been promoted. Through his research students and his professional activities, he has contributed significantly to the broadening horizon of chemical engineering. □

ChE book reviews

MASS TRANSFER IN ENGINEERING PRACTICE

By Aksel L. Lydersen

John Wiley & Sons, 1983, xiii + 321 pgs. \$39.95

Reviewed by F. L. Rawling, Jr.

E.I. Du Pont de Nemours & Co., Inc.

This book is a companion volume to the author's previous book "Fluid Flow and Heat Transfer" (John Wiley & Sons, 1979). The aim of the present volume is to present a short refresher course in those areas of unit operations specifically dealing with mass transfer. The book consists of eight chapters: an introductory chapter on the principles of diffusion and seven chapters covering distillation, gas absorption and desorption, liquid-liquid extraction and leaching, humidification, drying of solids, adsorption and ion exchange, and crystallization. The introductory chapter on the principles of diffusion provides a summary of the major equations together with a short discussion of the various types of diffusion, i.e. diffusion with bulk of mass in motion, eddy diffusion, molecular diffusion in liquids, etc. A short discussion of the two film theory and the penetration theory is also presented. No attempt is made at providing a fundamental treatment of the subject of diffusion; rather, reference is made to the literature. Several problems, typical of those encountered in industry are worked out in detail. There are four problems to be worked by the reader. The chapter ends with a good bibliography, although half the references are pre-1970.

Approximately two-thirds of the book is con-

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OKLAHOMA STATE UNIVERSITY

Chemical Engineering: Assistant, Associate, or Full Professor Position. This is a tenure-track position and will be approximately half-time teaching and half-time research. We will help the successful candidate establish research by providing initiation funds, co-investigation opportunities with senior faculty and proposal preparation-processing assistance from our Office of Engineering Research. Candidates must possess an earned Ph.D. from an accredited Department or School of Chemical Engineering or have a Ph.D. in related areas and have strongly related qualifications. We welcome applications from candidates with competencies and interest in any field of chemical engineering, but especially seek those with strengths in design and computer applications. This position is available as early as July 1984. Applications will be received through March 16, 1984. Please send your resume and list of three references to Professor Billy L. Crynes, Head, School of Chemical Engineering, 423 Engineering North, Oklahoma State University, Stillwater, OK 74078. Calls for additional information invited. OSU is an equal opportunity/affirmative action employer.

cerned with staged operations, reflecting the industrial importance of this type of process. In general, each chapter follows the same outline: a short discussion of the theory involved together with the relevant equations, a discussion of the unit operation presenting the assumptions involved and the major design equations, a very general discussion on the various types of equipment employed, a series of worked examples, a set of problems to be worked by the reader, and a bibliography.

The worked examples in each chapter make this book worthwhile. They are well chosen to illustrate industrial problems and are worked out in detail, giving the assumptions and reasoning involved in arriving at a solution. In a few instances, a programmable calculator (Hewlett-Packard) is used in the solution of a problem. The calculator program is given.

I believe the book fulfills its goal, i.e. a refresher course in mass transfer. The many references adequately direct the user to the fundamental literature. Practicing engineers faced with a problem in an area of mass transfer that they have not been involved with for some time will find this a good, succinct review. Students will find the worked examples illuminating. Instructors should find this book to be a useful adjunct to their course. □

A GRAND SALE: \$12 For A Dozen Experiments In CRE

ZHANG GUO-TAI* AND
HAU SHAU-DRANG**
*Oregon State University
Corvallis, OR 97331*

WE HAVE NOTICED THAT undergraduate chemical engineering laboratories in the United States commonly make use of experiments in unit operations, instrumentation and control; but that experiments in chemical reaction engineering (CRE) are very rare. This is understandable because such experiments usually require an advanced level of understanding, are rather complex in set up, and more involved to operate.

We would like to introduce a whole class of experiments which require very simple and inexpensive equipment and which illustrate one of the basic problems of chemical reaction engineering: the development of a kinetic rate equation from laboratory data. In essence, the student takes laboratory data, guesses a kinetic equation, tests its fit to the data and, if this is satisfactory, determines the corresponding rate constants.

Basically, we use a hydraulic analog. We will illustrate this with the simplest case; the fitting of a first order decomposition, $A \rightarrow R$.

Connect an ordinary glass capillary to a burette as shown in Fig. 1. Fill the burette with water, at time zero let the water flow out, and record the change in volume as time progresses.

We would like to introduce a whole class of experiments which require very simple and inexpensive equipment and which illustrate one of the basic problems of chemical reaction engineering.

*On leave from Shanghai Institute of Chemical Technology, China.

**On leave from Sichuan University, Chengdu, China.

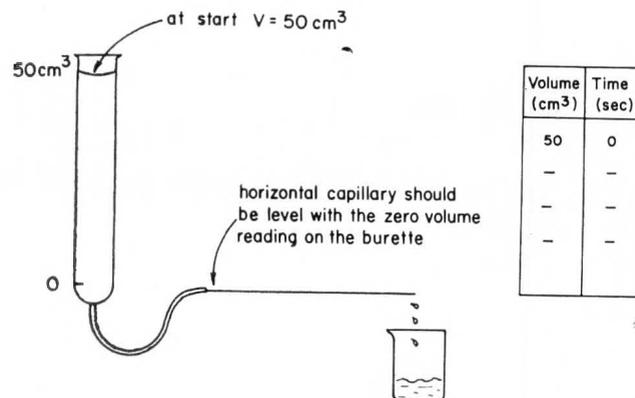


FIGURE 1. Experimental set up to represent the first order decomposition of reactant A, or $A \rightarrow R$.

The student is told to view the experiment of Fig. 1 as a batch reactor in which reactant A disappears to form product R. The volume reading on the burette in cm³ is to be considered as a concentration of reactant in mole/m³. Thus the experiment of Fig. 1 is to be treated as shown in Fig. 2.

By following the reactant concentration (actually the volume of water in the burette) versus time the student is to determine the order of reaction and the value of the rate constant. If the experiment is set up properly, one will find that the data fits first order kinetics.

The student sooner or later guesses first order kinetics, integrates the rate equation to give $\ln(C_0/C) = kt$, plots the logarithm of concentration versus time, and from this evaluates the rate constant. Thus he learns how to test kinetic models. Of course, the length and diameter of capillary will determine the value of the rate constant.

The experiment is so simple and quick to do one can incorporate a lesson in statistical analysis with it. Ask the student to repeat the experiment

a number of times, find the rate constant, and also the 95% confidence interval for the rate constant.

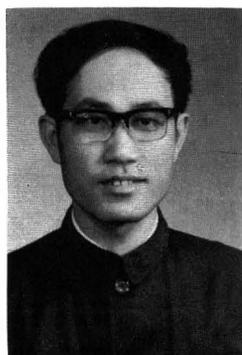
This is the simplest of a whole class of experiments that can be done with burettes and capillaries. Fig. 3 shows some of the many other reaction schemes that may be used.

There may be more than one way to test a rate form and fit the rate constants. It challenges the student's initiative and ingenuity to see how he approaches his particular problem. For example: for reactions in series, $A \rightarrow R \rightarrow S$ he can try to follow the concentrations directly, he may follow concentration ratios and fit them to charts as shown in Levenspiel [1], or he may try to use the conditions when the intermediate hits its maximum value. He soon finds that some approaches are much more discriminating than others.

SUGGESTIONS FOR SETTING UP THE EXPERIMENTS

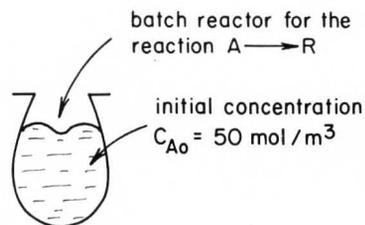
WE HAVE TESTED ALL THE experimental variations of Fig. 3 in the laboratory ourselves, and we have found that observation of the following simple precautions will result in excellent agreement of experiment with theory.

- Be sure that the capillary outlet is level with the zero line of the burette. Check this by filling the burette



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Reactant concentration (mol/m ³)	Time (sec)
50	0
—	—
—	—
—	—

FIGURE 2. Reactor analog to the hydraulic experiment of Fig. 1.

- and letting water run out until equilibrium is achieved.
- Do not have any restriction between burette and capillary comparable with that of the capillary itself.
- Verify that laminar flow exists in the capillary. For an ordinary capillary and burette this condition is well satisfied.
- Before starting an experiment pour water through the burettes so as to wet them. Also see that water does not flow back along the bottom of the capillary. Use a rubber band or a Chinese teapot spout dripper at the capillary outlet.
- If the capillary is not long enough then the run time will be awkwardly short; if too long, a lot of time is wasted: The following suggestions are convenient time scales and capillary lengths.

Let T_1 be the time required for the water in the first burette to drop to half its initial height and let the corresponding length of capillary be L_1 .

For the first experiment of Fig. 3 we find that $T_1 = 30-40$ sec is about right. For other experiments the appropriate time scales and capillary lengths are shown in Table 1.

- By preparing a number of capillaries and by using

TABLE 1
Recommended experimental conditions

Reaction Scheme Shown in Fig. 3	T_1 (sec)	Capillary length
Case 1	30-40	L_1
Case 2	20-30	$L_2 = 2-6 L_1$
Case 3	30-40	$L_3 = 2-4 L_1$
Case 4	20-30	$L_2 = 4 L_1, L_3 = 2-4 L_1$
Case 5	30-40	$L_3 = 2-4 L_1, L_4 = 2 L_1$
Case 6	20-30	$L_2 = 4-5 L_1, L_3 = 2-4 L_1$
Case 7	20-30	$L_2 = 4 L_1, L_3 = 2-4 L_1, L_4 = 8-10 L_1$
Case 8a,b	30-40	L_1
Case 9	20-30	$L_3 = 4 L_1$
Case 10	30-40	$L_3 = 4 L_1$
Case 11a,b	30-40	$L_3 = 3-4 L_1$
Case 12	30-40	$L_2 = 2-4 L_1, L_3 = 6-8 L_1$

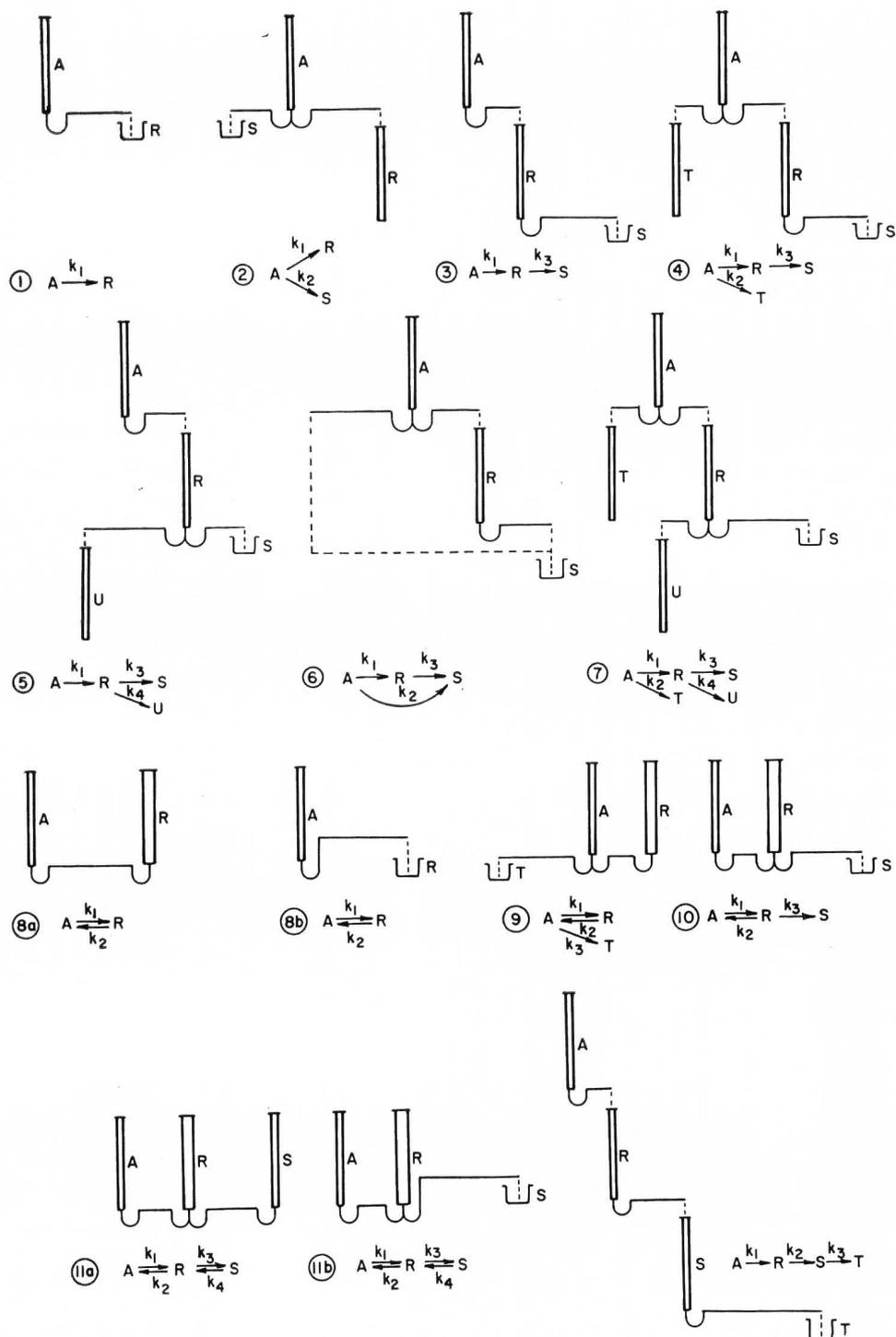


FIGURE 3. Some reaction schemes.

NOTES: In 8a, 9, 10, 11, use different diameter burettes to obtain different rate constants for the forward and reverse reactions. Be sure to take the volumetric burette reading, not height.

8b. One can use just one burette if one locates the capillary at a height above the zero reading on the burette.

11b. One can use 2 burettes if one locates the second capillary somewhat above the zero reading on the burettes.

various combinations of burettes the laboratory instructor can insure that no two laboratory groups will have the same experiment to perform, even in the giant classes which are now being processed.

Finally, a nice feature of this set of experiments is that the student most likely will be led to perform an integration of the performance equation for the batch reactor before he can test his guess with experiment.

CONCLUSION

WE HAVE SHOWN HOW A FEW burettes and capillaries, properly connected, can be the basis for a large number of simple experiments to teach the principles of data fitting in chemical reaction engineering. These experiments may be simple but they are not trivial. □

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APPENDIX

1. Many of the kinetic models of Fig. 3 (cases 1 to 6) are special cases of the Denbigh reaction scheme (case 7). The integrated form for this kinetic model, after appropriate manipulation is found to be

$$\frac{C_A}{C_{A,0}} = \exp(-K_1 t)$$

$$\frac{C_R}{C_{A,0}} = \frac{k_1}{K_2 - K_1} [\exp(-K_1 t) - \exp(-K_2 t)]$$

$$\frac{C_T}{C_{A,0}} = \frac{k_2}{K_1} [1 - \exp(-K_1 t)]$$

$$\frac{C_S}{C_{A,0}} = \frac{k_1 k_3}{(K_2 - K_1)} \left[\frac{1 - \exp(-K_1 t)}{K_1} - \frac{1 - \exp(-K_2 t)}{K_2} \right]$$

$$\frac{C_U}{C_{A,0}} = \frac{k_1 k_4}{(K_2 - K_1)} \left[\frac{1 - \exp(-K_1 t)}{K_1} - \frac{1 - \exp(-K_2 t)}{K_2} \right]$$

where

$$K_1 = k_1 + k_2$$

$$K_2 = k_3 + k_4$$

The conditions when the intermediate is at its

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maximum value are then

$$\frac{C_{R,max}}{C_{A,0}} = \frac{k_1}{K_1} \left[\frac{K_1}{K_2} \right]^{K_2/(K_2 - K_1)}$$

and

$$t \text{ (for } C_{R,max}) = \frac{\ln(K_2/K_1)}{K_2 - K_1}$$

These expressions may be useful for the instructor as a check of the students work.

2. All the kinetic equations in Fig. 3 involve systems of first order reactions and are conveniently solved, either by integration or by computer simulation for those who know how to talk to these machines. In a later paper we will consider non-linear systems and reaction orders different from unity. □

ACKNOWLEDGMENTS

We would like to thank our advisor, Professor Levenspiel for suggesting that we develop this series of experiments, and we would like to recognize Professor Jodra of the University of Madrid for indirectly bringing this type of experiment to our attention.

TWO COMPUTER PROGRAMS FOR EQUIPMENT COST ESTIMATION AND ECONOMIC EVALUATION OF CHEMICAL PROCESSES

CARLOS J. KURI AND
ARMANDO B. CORRIPIO
*Louisiana State University
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IN RECENT YEARS SEVERAL cost estimation and economic evaluation computer programs have been developed, including those associated with ASPEN [2, 3, 4], Monsanto's FLOWTRAN [10], Purdue's PCOST [11], and others. However, the fact that these programs are not readily available to most colleges and universities motivated this work: the development of a cost estimation and economic evaluation computer program with the latest information in the field, easy to use and by all means suited to fulfill the requirements of a senior process design course.

The algorithms used for the cost estimation computer program were obtained from the ASPEN Project, eleventh, thirteenth and fourteenth quarterly progress reports [2, 3, 4]. These algorithms are based on cost data for 1979.

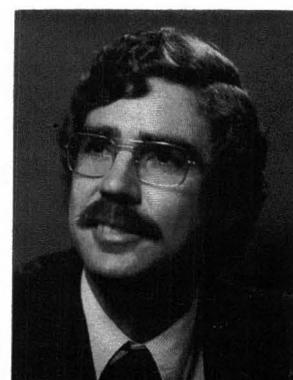
EQUIPMENT COSTING PROGRAM

The equipment costing program is modular in design so that it is relatively easy to add equipment classes as new costing models are developed. It is also relatively easy to update the cost correlations for existing equipment classes without affecting other classes. A schematic diagram of the program modular structure is given in Fig. 1.

A feature of the general design that is worth mentioning is the procedure for handling input data errors. When an error occurs in the specifications for a given equipment item, the calculated cost of that item is the only one affected. In other words, the program can recover and continue to calculate the costs of the items that follow. This



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Armando B. Corripio is professor of chemical engineering at Louisiana State University. For the past fourteen years he has taught courses and directed research in the areas of computer process control, automatic control theory and process simulation and optimization. He has been actively involved in consulting for several industrial organizations, has authored and coauthored over seventy technical articles and presentations, and has presented over seventy short courses and seminars for ISA, AIChE, and other organizations. He is a member of ISA, AIChE, The Society for Computer Simulation, and other professional and honorary societies. He is also a registered professional engineer, married, and proud father of four children. In his spare time he plays tennis, swims and coaches a youth soccer team. (R)

procedure is designed so that the program can detect as many input data errors as possible in a single run, as opposed to detecting one error per run.

Equipment Cost Correlations. The basic cor-

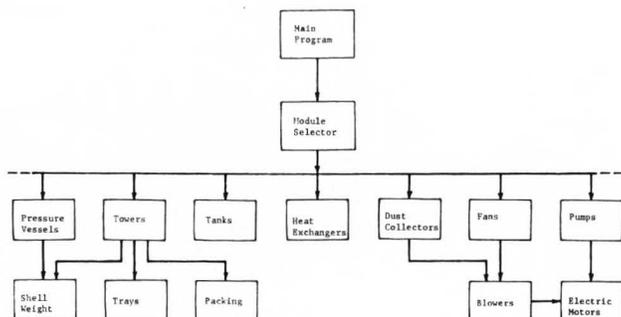


FIGURE 1. Modular structure of equipment cost estimation program.

relation for the base cost of a piece of equipment is usually of the form:

$$\ln C_B = a_1 + a_2 \ln S + a_3 (\ln S)^2$$

where C_B = the base equipment cost per unit

S = the equipment size (or duty parameter) per unit

a_1, a_2, a_3 = the cost correlation coefficients.

The base cost is used as a basis to compute the actual estimated cost, the installation materials cost and the installation labor hours. It is usually the cost of the equipment in carbon steel for a common design type and pressure rating and thus independent of the equipment design type, the material of construction and the pressure rating. The estimated equipment cost is then calculated by the following formula

$$C_E = C_B f_D f_M f_P$$

where C_E = the estimated equipment cost

f_D = the design type cost factor (if applicable)

f_M = the material of construction cost factor

f_P = the pressure rating factor (if applicable)

If the equipment size is larger than the correlation upper limit, the function is extrapolated at constant cost per unit size

$$C_B = C_{Bmax} (S/S_{max})$$

where C_{Bmax} = the maximum cost of the maximum size

S_{max} = the maximum size for which the correlation is valid.

If the equipment size per unit is less than the

Two computer programs have been developed which are suitable for use by students in process design courses. The equipment cost estimation program is flexible, easy to use and based on the latest cost correlations available, those from project ASPEN.

correlation lower limit, the cost per unit is set equal to the minimum

$$C_B = C_{Bmin}$$

where C_{Bmin} = the minimum cost for which the correlation is valid.

The equipment cost is adjusted to the specified escalation index in order to correct for inflation. The Chemical Engineering Fabricated Equipment Index [5] is used for this purpose.

Input Data Specifications. A sample of the input specifications for the equipment costing program is shown in Table 1. The data on this table illustrate the costing of seven different equipment items, organized in card-image (80-column) records. The first record of specifications for each equipment item is easily recognized by the asterisk (*) in column one. This code provides a key for the detection by the program of missing records or of records out of sequence.

Discussion of Cost Estimation Results. The results of the equipment cost estimation program for the items specified in Table 1 are compared in Table 2 with costs for similar equipment items that have been reported in the literature. Most of the literature costs are from Peters and Timmerhaus [7] which is a widely used text for process design courses. All of the literature costs have been escalated to a Chemical Engineering Fabricated Equipment Index of 259.9 (1979) for comparison. The agreement between the program

TABLE 1
Sample of Input Data for Equipment Costing Program.

Code	Description	Quantity	Cost	Escalated Cost	Index
*CDCK101DCCY M3/SN/M2	CYCLONE	12	8.50	6.90E3	1979
*CFAK102 M3/SN/M2 K	INDUSTRIAL FAN	1	16.5	1870. 323.	
*CHEK103 F2N/M2	HEAT EXCHANGER	31	1000.	1.034E6	
*CPVK104PVH0 FF	HORIZONTAL VESSEL	4	9.	30. .041666	
*CPLK105 LBF3F3/1 N/M2	CENTRIFUGAL PUMP	2	62.4	47.472	6.9E05
*CTAK106 . I M3	FIELD-ERECTED TANK	1	1.13	1892.5	
*CTOK107TOTR FF	TRAY TOWER	2	14.	130.	75.
*SUM		2	3	0.20	
*END					

costs and the literature costs is quite good in most cases and within the accuracy of preliminary study estimates. The largest discrepancies are in the cyclone and tray tower costs. For each of these cases the graphs in Peters and Timmerhaus had to be extrapolated, which may account for the discrepancy.

ECONOMIC EVALUATION PROGRAM

An acceptable plant design must present a process that is capable of operating under conditions that will yield a profit. The purpose of the economic evaluation computer program is to calculate two profitability indices: the net present value and the internal rate of return. These two indices are based on discounted cash flow techniques, taking into consideration the time value of money.

Net Present Value (NPV)

$$NPV = \sum_{k=0}^n \frac{NCF_k}{(1+i)^k(1+RINF)^k}$$

where NCF_k = the net cash flow for the k^{th} year
 i = the effective annual rate of return
 $RINF$ = the annual inflation rate

n = the number of years of duration of the project.

Internal Rate of Return (IRR). This is the rate of return that equates the present value of the expected future cash flows or receipts to the initial capital outlay. Normally a trial and error procedure or root finding technique is required to find the discount rate that forces the NPV to zero.

To be more realistic in the calculation of these two indices of profitability, the effect of inflation is included. Failure to at least try to predict inflation rates and take them into account can greatly distort project economics, especially at the double-digit rates that have become common throughout the world.

The procedure used in the program in computing the indices of profitability is described in the text by Bussey [1].

Economic Evaluation Program Results. Results of the economic evaluation program for a sample case are presented in Table 3. The problem is to estimate the profitability of a solids processing plant. Total purchased equipment cost is estimated at \$3,200,000, with an economic life of 10 years. An interest rate of 10%, inflation rate of 8% and

TABLE 2
Comparison of Equipment Cost Estimation Results

<u>Equipment Item</u>		<u>Program Cost, 1979</u>	<u>Literature Cost, 1979</u>	<u>Reference</u>
1. Cyclone	8.5 m ³ /s (18,000 cfm); 6,900 N/m ² (28 in water); Excluding blower and motor	\$ 3,380	\$ 5,300	Peters and Timmerhaus [7], (p. 599). Extrapolation required.
2. Fan	16.50 m ³ /s (35,000 cfm); 1,870 N/m ² (7.5 in water); 323°K (121 F); Carbon steel; Explosion-proof motor; Belt drive coupling	\$ 8,360	\$ 8,500	Richardson [9].
3. Heat Exchanger	1,000 ft ² ; 1.034•10 ⁶ N/m ² (150 psi); Stainless 316; U-Tube	\$ 29,100	\$ 33,000	Peters and Timmerhaus [7], (p. 670).
4. Horizontal Vessel	1.034•10 ⁶ N/m ² (150 psi); 9 ft diameter; 30 ft long	\$ 28,600	\$ 25,500	Pikulik and Diaz, [8].
5. Centrifugal Pump	6.9•10 ⁵ N/m ² (100 psi); 62.4 lb/ft ³ ; 23.74 ft ³ /min (178 GPM); Totally enclosed fan-cooled electric motor	\$ 1,830	\$ 1,800	AVS (American Volunteer Standard) Peters and Timmerhaus [7], (p. 557).
6. Storage Tank	1,893 m ³ (500,000 gal); Carbon steel	\$ 79,600	\$ 71,000	Cone roof tank Peters and Timmerhaus [7], (p. 573).
7. Tray Tower	14 ft diameter; TTL = 130 ft long; Stainless 304; 75 Valve trays	\$859,000	\$657,000	Peters and Timmerhaus [7], (p. 768). Extrapolation required.

TABLE 3
Sample of Output Results for Economic Evaluation
Program. Profitability.

END OF YEAR	NET SALES	OPERATING COST	GROSS INCOME	INTEREST EXPENSE	DEPRECIATION EXPENSE	NET INCOME AFTER TAX	SECTION 1231 CASH FLOW	NET CASH FLOW	PRESENT VALUE INCREMENT	
0	0.	0.	0.	0.	0.	0.	-4404706.	-4404706.	-4404706.	
1	13933488.	11581918.	2351570.	1027764.	2431999.	-576260.	-644883.	1210855.	934302.	
2	17424176.	13894143.	3530033.	963276.	1958071.	316517.	-709371.	1565215.	931891.	
3	21669312.	16668485.	5000827.	892339.	1576499.	1316634.	-780308.	2112824.	970621.	
4	26790096.	19977360.	6812736.	814308.	1269284.	2459155.	-858339.	2870099.	1017369.	
5	33256672.	24096912.	9159760.	728474.	1021936.	3852862.	-944173.	3930624.	1075074.	
6	35917184.	26024640.	9892544.	634056.	822790.	4386562.	-1038591.	4170761.	880213.	
7	38790544.	28106608.	10683936.	530197.	769855.	4879619.	-1142449.	4507024.	733936.	
8	41893760.	30355104.	11538656.	415952.	769855.	5383481.	-1256694.	4896641.	615265.	
9	45245248.	32783504.	12461744.	290283.	769855.	5928835.	-1382363.	5316326.	515431.	
10	48864816.	35406160.	13458656.	152047.	769855.	6519112.	1001752.	8290718.	620221.	
NET PRESENT VALUE AT 20.0 PERCENT RATE OF RETURN						3889614.				
DISCOUNTED CASH FLOW RATE OF RETURN (PERCENT)						38.19				
INFLATION RATE (PERCENT)						8.00				
TAX RATE (PERCENT)						48.00				

tax rate of 48% are specified. Base net annual sales are estimated at \$22,634,000 with a fixed annual operating cost of \$3,200,000 and a variable annual operating cost of \$13,200,000 at 100% production. The variable annual operating cost is assumed to be proportional to the production rate. Percentages of production for the ten years of operation are as follows: 57, 66, 76, 87, 100, 100, 100, 100, 100, 100. Additional input data are the percentage of total investment financed by debt, 70%, the life of the loan, 10 years, and the depreciable life, 10 years. Depreciation is computed by the double-declining balance method with a salvage value of \$320,000. The program input data are entered in free format.

The columns of the cash flow table (Table 3) summarize the major components of the cash flow for each year of operation. The numbers represent annual amounts in inflated dollars.

Case Studies. A series of results obtained with the economic evaluation program are summarized in Tables 4 and 5. The effect of inflation on the internal rate of return (IRR) and on the net present value (NPV) is illustrated in Table 4 for various financing and tax situations. Cases 1 through 4 represent "after-tax return" with a tax rate of 48%, while cases 5 through 8 represent "before-tax return," that is, tax rate equal to

zero. The rest of the input data are the same as for the sample problem described above.

Comparison of cases 1 and 2 and of cases 5 and 6 show the effect of inflation on a heavily debt-financed project. The increase in both the IRR and NPV is due to the fact that the net income from the project inflates while the loan payments remain constant. In other words, most of the inflation losses are passed on to the financing organization. Comparison of cases 3 and 4 show that the effect of inflation on the IRR and NPV reverses when the project is 100% equity financed. This is due to taxes which increase with inflation

TABLE 4
Effect of Inflation on the Rate of Return
and the Net Present Value

	Inflation Rate, %	% Debt	Tax Rate, %	IRR %	NPV @ 20% k\$
1.	0	70	48	35.76	3,250
2.	8	70	48	38.19	3,890
3.	0	0	48	17.17	-1,580
4.	8	0	48	15.56	-2,400
5.	0	70	0	46.46	7,620
6.	8	70	0	51.17	9,180
7.	0	0	0	26.56	4,350
8.	8	0	0	26.32	4,130

as depreciation remains constant. Notice the negative NPV for both of these cases. This is because the actual IRR is less than the 20% rate of return used to calculate the NPV. The obvious advantage of debt financing in this problem is due to the low interest rate on the loan (10%). Finally, comparison of cases 7 and 8 shows that inflation has no effect on the before-tax return when there is no loan. This is because all of the remaining cash flow items are assumed to inflate at the same rate. Depreciation has no effect on the before-tax returns.

The effect of the depreciation method on the IRR and on the NPV is shown in Table 5. Both double-declining balance and sum-of-the-years' digits produce similar results and are superior to the straight line method. This is because the depreciation allowance is accelerated in the early years of the project reducing taxes and shifting after-tax income to the early years where it counts

TABLE 5
Effect of Method of Depreciation on the Rate of Return and the Net Present Value

Depreciation Method	IRR, %	NPV @ 20% k\$
Straight-line	34.22	3,300
Double-declining balance	38.19	3,890
Sum-of-the-years' digits	38.30	3,943

Percent debt: 70%
Tax Rate: 48%
Inflation Rate: 8%

more. The double-declining balance method used by the program switches automatically to straight-line in the later years of the project as allowed by the rules of the Internal Revenue Service.

CONCLUSIONS

Two computer programs have been developed which are suitable for use by students in process design courses. The equipment cost estimation program is flexible, easy to use and based on the latest cost correlations available, those from project ASPEN. The economic evaluation program frees the student from the tedious trial-and-error calculations which are involved in the determination of the internal rate of return. The program is realistic as it accounts for depreciation, income taxes and inflation. □

ACKNOWLEDGMENT

The authors wish to express their appreciation

to the staff of project ASPEN, MIT Energy Laboratory, for the cost correlations used in the equipment cost estimation program, and to Banco Central de Reserva de El Salvador for the support of Mr. Kuri.

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"Surface Chemistry of Froth Flotation," Jan Leja; Plenum Publishing Corp., New York 10013; 758 pages, \$69.50 (1982)

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In Memoriam

J. H. ERBAR

John Harold Erbar, 51, professor of chemical engineering at Oklahoma State University, died September 17, 1983.

Born in El Reno, OK, Erbar earned all of his academic degrees in chemical engineering at Oklahoma State University. Following service in the U.S. Army, he joined Standard Oil Company and worked in several research positions. He joined the OSU faculty as an assistant professor of chemical engineering in 1962 and was named full professor in 1969. He was named Teacher of the Year in 1970-71 and again in 1982-83.

Dr. Erbar was recognized internationally as an expert in computer applications in chemical engineering and taught courses in chemical engineering design, thermodynamics, fluid flow, stagewise



operations and others. He was a member of Omega Chi Epsilon, AIChE, ACS, ASEE, and various Oklahoma and national societies for professional engineers. He was a registered professional engineer in Oklahoma.

He is survived by his widow, Ruth, and a daughter and a son.

ChE stirred pots

The Limerick Metric Applied to Thermodynamics

*The subject of Thermodynamics,
'Tis true, is not for pedantics.
For, tho work must be done
And sweat be not shunned,
Insight requires more than mechanics.*

*O'r the four Laws stands Confusion,
As their numbering is all but illusion;
For the first is not first,
Tho the first is well vers'd,
And the last is not fourth—how amusin'!*

*The relations of Maxwell are infamous
For prompting ill-natured remarks most
boisterous.*

*Their exactness is trying,
Their permutations vying
With other companions more amorous.*

*The compressibility of liquids and gases
Is oft devious to lads and lasses.
Relating P, V, and T
Seems difficult to see
Without perturbing the masses.*

*Some students have little capacity
For understanding fugacity.
Their tendency to flee
Is paradoxical, to me,
And how will they develop tenacity?*

*The structure of phase diagrams abound
With complexities horribly profound.
Solid fluid, triple critical,
And others more mythical,
Its very dimensions can naught but astound.*

*T'was once a Chem Engineer grasping
For the concept of entropy dashing
To proverbial heights;
But try as he might,
There seemed little hope of his passing!*

J. M. Haile
Clemson University
Clemson, SC 29631

NEW ADSORPTION METHODS*

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ADSORPTION AND ION EXCHANGE systems are used for a variety of separations and purifications in industry. Many different operational techniques have been proposed for these separation schemes. In this review we will first develop a simple method (suitable for undergraduate and graduate students) for following the movement of a solute in an adsorption or ion exchange system. Then this solute movement will be used to study a variety of operational methods. Much of this paper appeared previously [23].

SOLUTE MOVEMENT

Consider first a bed of porous particles. The particles have an interparticle (between different particles) porosity of α and an intraparticle (within a given particle) porosity of ϵ . The total porosity of the bed for small molecules is $\alpha + (1-\alpha)\epsilon$. This is illustrated in Fig. 1. In addition, large solutes will not be able to penetrate all of the intraparticle void space. The fraction of volume of the particle which any species can penetrate is K_d . For a non-adsorbed species, K_d can be determined from

$$K_d = \frac{V_e - V_o}{V_i} \quad (1)$$

where V_e is the elution volume, V_o is the external void volume between the particles, and V_i is the

*Presented at ChE Division ASEE Summer School, August, 1982.

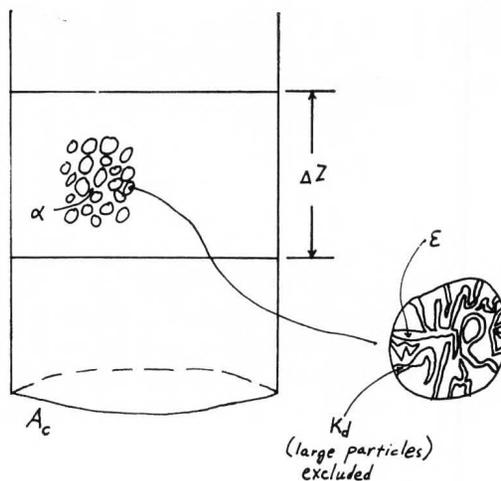


FIGURE 1. Porosities in packed bed.

internal void volume. When the molecules are small and can penetrate the entire interparticle volume, $V_e = V_i + V_o$ and $K_d = 1.0$. When the molecules are large and can penetrate none of the interparticle volume, $V_e = V_o$ and $K_d = 0$.

As solutes migrate through the bed they can be in the mobile fluid in the external void volume, in the stagnant fluid inside a particle, or sorbed to the particle. The only solutes which are moving towards the column exit are those in the mobile fluid. Consider the movement of an incremental mass of solute added to a segment of the bed shown in Fig. 1. Within this segment this incremental amount of solute must distribute to form a change in fluid concentration, Δc , and a change in the amount of solute adsorbed, Δq . The amount of this increment of solute in the mobile fluid compared to the total amount of solute increment in this segment is

$$\frac{\text{Amt. in mobile fluid}}{\text{Total amt. in segment}} = \frac{\text{Amt. in mobile fluid}}{\text{Amt. in: (Mobile fluid + stationary fluid + sorbed)}} \quad (2)$$

which is

$$\frac{\text{Amt. in mobile fluid}}{\text{Total amt. in segment}} = \frac{(\Delta z A_c) \alpha \Delta c}{(\Delta z A_c) \alpha \Delta c + (\Delta z A_c) (1-\alpha) \epsilon \Delta c K_d + (\Delta z A_c) (1-\alpha) (1-\epsilon) \rho_s \Delta q K_d} \quad (3)$$

The solid density, ρ_s , is included in Eq. (3) to make the units balance. A_c is the cross sectional area, and z is the axial distance.

If fluid has a constant interstitial velocity, v , then the average velocity of the solute in the bed (the solute wave velocity) is just v times (relative amount of time the incremental amount of solute is in the mobile phase). Assuming a random process of adsorption, desorption and diffusion in and out of the stagnant fluid, the solute wave velocity becomes

$$u_{\text{solute}} = v \left[\frac{\text{amount solute in mobile phase}}{\text{total amount solute in column}} \right] \quad (4)$$

or, after rearrangement

$$u_{\text{solute}}(T) = \frac{v}{1 + [(1-\alpha)/\alpha] \epsilon K_d + [(1-\alpha)/\alpha] (1-\epsilon) \rho_s (\Delta q / \Delta c) K_d} \quad (5)$$

Eq. (5) represents a crude, first order description of movement of solute in the column. With a few additional assumptions this equation can be used to predict the separation in the system.

The most important assumption, and the assumption least likely to be valid, is that the solid and fluid are locally in equilibrium. Then Δq will be related to Δc by the equilibrium adsorption iso-

therm. This assumption allows us to ignore mass transfer effects. The second assumption is that dispersion and diffusion are negligible; thus, all of the solute will travel at the same average solute velocity. These assumptions greatly oversimplify the physical situation, but they do allow us to make simple predictions. As long as we don't believe these predictions must be exactly correct, the simple model which results can be extremely helpful in understanding separation techniques.

For undergraduate students we limit the theory to simple linear equilibrium of the form

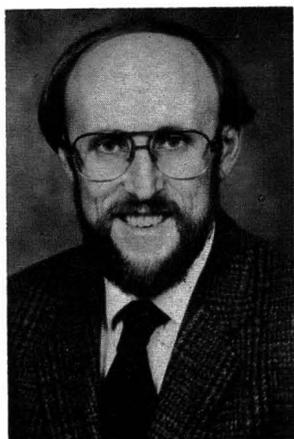
$$q = A(T) c \quad (6)$$

where q is the adsorbed solute concentration,

$A(T)$ is the equilibrium constant which is a function of temperature, and c is the solute concentration in the fluid.

For common adsorbents the amount of material adsorbed decreases as temperature is increased. Thus $A(T)$ is a monotonically decreasing function of temperature. With linear equilibrium $\Delta q / \Delta c = A(T)$, and Eq. (5) becomes

$$u_{\text{solute}}(T) = \frac{v}{1 + [(1-\alpha)/\alpha] \epsilon K_d + [(1-\alpha)/\alpha] K_d (1-\epsilon) \rho_s A(T)} \quad (7)$$



Phil Wankat received his BSChE from Purdue and his PhD from Princeton. He is currently a professor of chemical engineering at Purdue. He is interested in teaching and counseling, has won several teaching awards at Purdue, and is a part-time graduate student in Education. Phil's research interests are in the area of separation process with particular emphasis on cyclic separations, two-dimensional separations, preparative chromatography, and high gradient magnetic separation.

For Eq. (7) the solute wave velocity is the same as the average solute velocity. Eq. (7) allows us to explore the behavior of solute in the column for a variety of operating methods.

Several facts about the movement of solute can be deduced from Eq. (5) or Eq. (7). The highest possible solute velocity is v , the interstitial fluid velocity. This will occur when the molecules are very large and $K_d = 0.0$. For small molecules $K_d = 1.0$, and with porous packings these molecules always move slower than the interstitial velocity even when they are not adsorbed. If adsorption is very strong the solute will move very slowly. When the adsorption equilibrium is linear, Eq. (7) shows that the solute velocity does not depend on the solute concentration. This is important and greatly simplifies the analysis for linear equilibria. If the equilibrium is nonlinear, $\Delta q / \Delta c$ will depend on the fluid concentration and Eq. (5) shows that the solute velocity will depend on concentration.

Nonlinear equilibrium will be considered later.

A convenient graphical representation of the solute movement is obtained on a plot of axial distance, z , versus time. Since the average solute molecule moves at a velocity of $u_{\text{solute}}(T)$, this movement is shown as a line with a slope u_{solute} . This is illustrated for a simple chromatographic separation in Fig. 2. Fig. 2A shows the feed pulse while Fig. 2B shows the solute movement in the column. The product concentrations predicted are shown in Fig. 2C. Note that this simple model does not predict dispersion or zone spreading, but does predict when the peaks exit.

If desired, zone spreading can be included, but will conceptually complicate the model. The advantage of this model is that it is simple and can be used to understand a variety of methods of operation.

EFFECTS OF CHANGING THERMODYNAMIC VARIABLES

Changes in temperature, pH, ionic strength or solvent concentration are often used to help desorb and elute the solute. Changes in these variables will change the equilibrium constant, A , in Eqs. (6) and (7). With temperature one can either use a jacketed bed and change the temperature of the entire bed (called the direct mode) or he can change the temperature of the inlet stream and have a temperature wave propagate through the column (called the travelling wave mode). For most of the other elution methods the travelling wave mode is used. Elution may be done either concurrently or countercurrently.

The wave velocities for chemicals added to the system can be obtained from Eq. (5) or (7). The

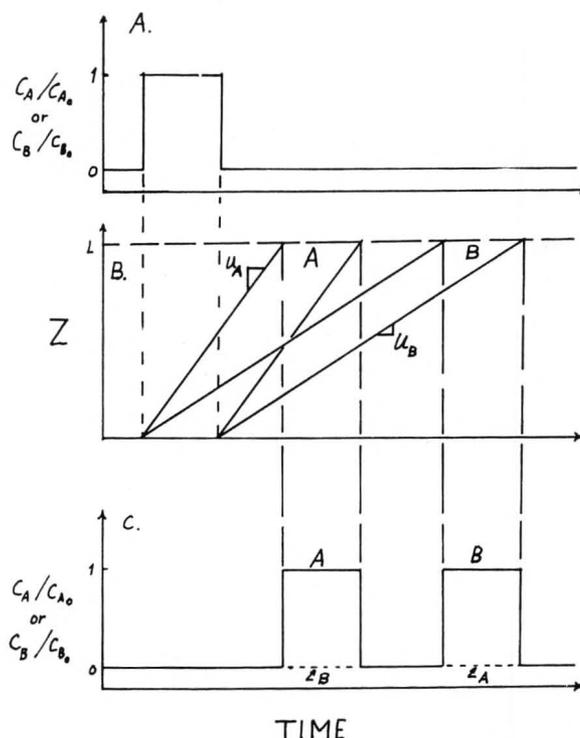


FIGURE 2. Solute movement model for isothermal chromatography: A) Feed pulse; B) Trace of solute movement in column; C) Product concentrations.

In Eq. (8) W is the weight of column wall per length and T_{ref} is any convenient reference temperature. The wall term is only important in laboratory scale columns. The velocity of the thermal wave in the column is just the ratio in Eq. (8) multiplied times the fluid velocity. After assuming local equilibrium so that $T_s = T_f = T_w$ and simplifying, we have

$$u_{\text{thermal}} = \frac{v}{1 + [(1-\alpha)/\alpha]\epsilon + [1-\alpha](1-\epsilon)C_s\rho_s + (W/A_c)C_w]/\alpha\rho C_f} \quad (9)$$

velocity at which temperature moves in the column (the thermal wave velocity) can be obtained from an energy balance. If we can ignore the heat of adsorption and heat of mixing and assume the column is adiabatic, then the energy in the mobile fluid compared to the total energy in mobile fluid, stationary fluid, solid and the column wall in a segment of the column is

$$\frac{\text{Energy in mobile phase}}{\text{Total energy in column segment}} = \frac{(\Delta z A_c) \alpha \rho_f C_f (T_f - T_{\text{ref}})}{[(\Delta z A_c) (\alpha + (1-\alpha)\epsilon) \rho_f C_f (T_f - T_{\text{ref}}) + (\Delta z A_c) (1-\alpha) (1-\epsilon) C_s \rho_s (T_s - T_{\text{ref}}) + (\Delta z W) C_w (T_w - T_{\text{ref}})]} \quad (8)$$

ment of the average solute molecule, Eq. (9) represents the average rate of movement of the thermal wave. A more exact analysis is needed to include dispersion and heat transfer rate effects.

On a graph of axial distance z versus time t the thermal wave will be a straight line with a slope u_{thermal} . Figure 3 illustrates elution using temperature for counter-current desorption. In this case a single solute is adsorbed. The feed flow is continued until just before solute breakthrough occurs. Then counter-current flow of a hot fluid is used to remove solute. Upon reversing the flow the fluid first exits at the feed temperature and the feed concentration. When the thermal wave breaks through, the temperature and concentration both jump. Since the adsorption equilibrium

constant is lower at high temperature the solute velocity can be significantly greater at the higher temperature. In actual practice the outlet temperature and concentration waves will be S-shaped curves because of the dispersion forces.

To complete the analysis of the traveling wave mode we need to consider the change in solute concentration when the adsorbent temperature is changed. The effect of temperature changes on solute concentration can be determined by a mass balance on a differential section of column Δz over which the temperature changes during a time interval Δt . This balance for one solute is

$$\alpha v \Delta t (c_2 - c_1) - [\alpha + K_d \epsilon (1 - \alpha)] (c_2 - c_1) \Delta z - (1 - \alpha) (1 - \epsilon) K_d \rho_s (q_2 - q_1) \Delta z = 0 \quad (10)$$

where 1 refers to conditions before the temperature shift and 2 to after the shift. In Eq. (10) the first term is the in-out term, the second term is accumulation of solute in the fluid, and the third term is accumulation of solute on the solid. To ensure that all material in the differential section undergoes a temperature change the control volume is selected so that $\Delta t = \Delta z / u_{\text{thermal}}$. The mass balance then becomes

$$\left(\alpha + \epsilon (1 - \alpha) K_d - \frac{\alpha v}{u_{\text{thermal}}} \right) (c_2 - c_1) + K_d (1 - \alpha) (1 - \epsilon) \rho_s (q_2 - q_1) = 0 \quad (11)$$

If we assume that solid and fluid are locally in equilibrium and that the equilibrium isotherm is linear, then Eq. (11) reduces to

$$\frac{c(T_H)}{c(T_C)} = \left(\frac{1}{u_{\text{solute}}(T_C)} - \frac{1}{u_{\text{thermal}}} \right) / \left(\frac{1}{u_{\text{solute}}(T_H)} - \frac{1}{u_{\text{thermal}}} \right) \quad (12)$$

... we will first develop a simple method (suitable for undergraduate and graduate students) for following the movement of a solute in an adsorption or ion exchange system. Then this solute movement will be used to study a variety of operational methods.

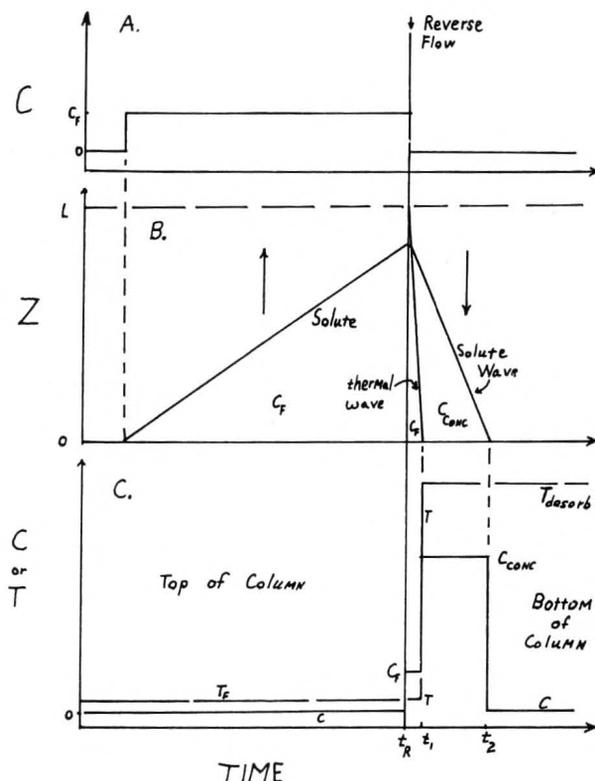


FIGURE 3. Solute movement model for adsorption followed by counter-current elution with a hot fluid: A) Inlet concentration and temperatures; B) Trace of solute and temperature movement in bed; C) Product concentrations and temperatures.

In the typical liquid system $u_{\text{thermal}} > u_{\text{solute}}(T_H) > u_{\text{solute}}(T_C)$, and $C(T_H) > C(T_C)$. Thus the solute is concentrated during elution. This concentration is calculated from Eq. (12), and was plotted on Fig. 3C. Note in Figs. 3A and 3C that the overall mass balance will be satisfied. If the equilibrium constant A does not change very much $u_{\text{solute}}(T_H) \approx u_{\text{solute}}(T_C)$ and there will be little change in concentration during elution. Since A is not usually strongly dependent on temperature, large temperature changes are required. An alternative is to use

The equations developed here can be rigorously derived from the governing partial differential equations by making a group of assumptions called the local equilibrium assumptions and then using . . . the method of characteristics.

a different eluant which has a major effect on A. Eqs. (11) and (12) are still valid but with u_{Eluant} replacing u_{thermal} .

In the direct mode the entire column is heated or cooled simultaneously. In this case u_{thermal} is essentially infinite and Eq. (12) simplifies to

$$\frac{c(T_H)}{c(T_c)} = \frac{u_{\text{solute}}(T_H)}{u_{\text{solute}}(T_c)} \quad (13)$$

For the usual adsorbent A(T) decreases (solute desorbs) as temperature increases. Thus u_{solute} increases and, as expected, Eq. (13) predicts that the solute concentration increases as temperature increases.

This completes the basic analysis procedure for the solute movement model for linear isotherms. As presented, this is not a rigorous mathematical model but was based on simple physical ideas. The equations developed here can be rigorously derived from the governing partial differential equations by making a group of assumptions called the local equilibrium assumptions and then using a mathematical method called the method of characteristics [1, 22]. Although some of the assumptions required for the rigorous development have been mentioned in passing, it will be helpful to list them explicitly here.

1. Homogeneous packing (no channeling).
2. Radial gradients are negligible.
3. Neglect thermal and pressure diffusion.
4. No chemical reactions except for sorption.
5. Neglect kinetic and potential energy terms.
6. No radiant heat transfer.
7. No electrical or magnetic fields.
8. No changes of phase except sorption.
9. Parameters are constant except for A.
10. Constant fluid velocity.
- 11a. Column is adiabatic, or
- 11b. Column is at controlled constant temperature.
12. Heat of adsorption is negligible.
13. Solutes do not interact.
14. Thermal and mass dispersion and diffusion are negligible.
15. Heat and mass transfer rates are very high so that fluid and solid are locally in equilibrium.
16. Equilibrium is linear.

This is a formidable list of assumptions. If any

of these assumptions are invalid the predictions can be way off. The most critical assumptions are the last three. Assumptions 14 and 15 cause the outlet concentrations and temperatures to show sharp jumps instead of the experimentally observed S-shaped curves. Alternate mathematical models which are more realistic but much more complex are reviewed by Sherwood *et al* [19]. Assumption 16 can also cause physically impossible predictions, but fortunately this assumption of linear equilibrium is easily relaxed (see the next section).

As we have seen this model greatly oversimplifies the actual fluid flow and heat and mass transfer processes occurring in the column. Because of this the predicted separation is always better than that obtained in practice. What is this model good for? The model is simple and can thus be used to analyze rather complex processes. The model does predict when the peak maximum will exit and thus is a good guide for setting operating variables. Since this model predicts the best possible separation, the model can be used to determine if, at its best, a separation scheme is of interest. Since the predictions made are qualitatively correct, as long as the model predictions are interpreted in a qualitative or at best semi-quantitative sense the model is very useful.

NONLINEAR SYSTEMS

If the equilibrium isotherm is nonlinear the basic structure developed here is still applicable, but we must use Eqs. (5) and (11) instead of (7) and (12). The solute velocity now depends on both temperature and concentration. Once a specific isotherm is determined it can be substituted into Eq. (5). For example, if the Freundlich isotherm

$$q = A(T)c^k \quad k < 1 \quad (14)$$

is used, then

$$\lim_{\Delta c \rightarrow 0} \frac{\Delta q}{\Delta c} = \left. \frac{\partial q}{\partial c} \right|_T = k A(T)c^{k-1} \quad (15)$$

and

$$u_{\text{solute}} = \frac{v}{1 + [(1-\alpha)/\alpha] \epsilon K_d + [(1-\alpha)/\alpha] K_d (1-\epsilon) \rho_s k A(T) c^{k-1}} \quad (16)$$

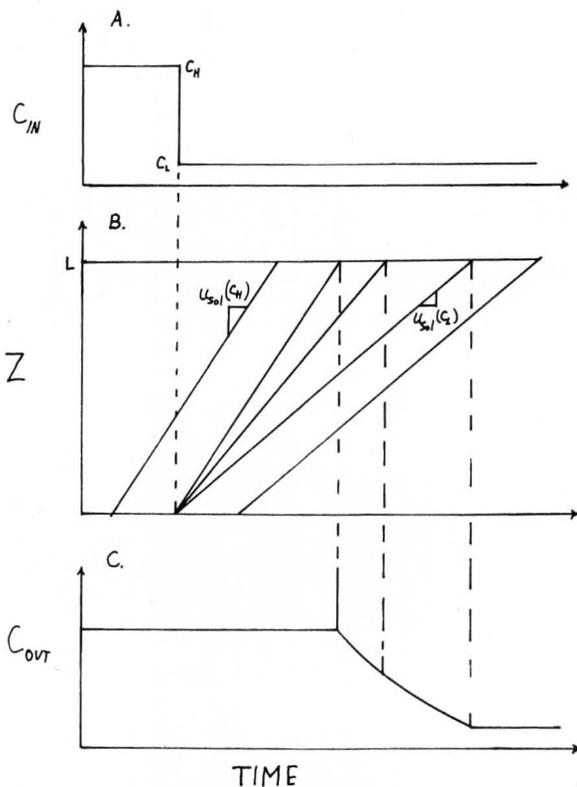


FIGURE 4. Diffuse waves: A) Inlet concentration; B) Solute movement; C) Outlet concentration.

A diffuse wave occurs when a concentrated solution is displaced by a dilute system. This is illustrated in Fig. 4 where the outlet wave concentrations are calculated. If we try the reverse (dilute solution displaced by a concentrated solution) then the limit does not exist since Δc has a finite value. A shock wave occurs. Another way of looking at this is Eq. (16) predicts a lower slope for dilute systems. When a concentrated solution displaces a dilute solution (Fig. 5A), the theory predicts that the solute lines overlap and two different concentrations occur simultaneously (Fig. 5B). This is physically impossible. To avoid this problem a mass balance is done on a finite section of the column of length Δz . This balance is the same as Eq. (10) except 1 refers to before the shock and 2 after the shock. Now we select the time interval $\Delta t = \Delta z / u_{\text{shock}}$ so that the shock has passed through the entire section. Solving for the shock wave velocity, we obtain

$$u_{\text{shock}} = \frac{v}{1 + [(1-\alpha)/\alpha] \epsilon K_d + [(1-\alpha)/\alpha] (1-\epsilon) K_d \rho_s [(q_2 - q_1)/(c_2 - c_1)]} \quad (17)$$

This is shown in Fig. 5C and the outlet concentration is calculated in Fig. 5D.

Nonlinear isotherms can result in interesting interactions when various shock and diffuse waves intersect. The mathematical principles involved in switching from differential to finite elements is also a good pedagogical tool for teaching graduate students. For graduate students I rigorously derive all these results using the local equilibrium model and the method of characteristics [19, 22].

COUNTER-CURRENT OPERATION I. Continuous Flow

In most chemical engineering unit operations continuous counter-current flow is used since it is usually the most efficient way to operate. Counter-current movement of solids and fluid is difficult

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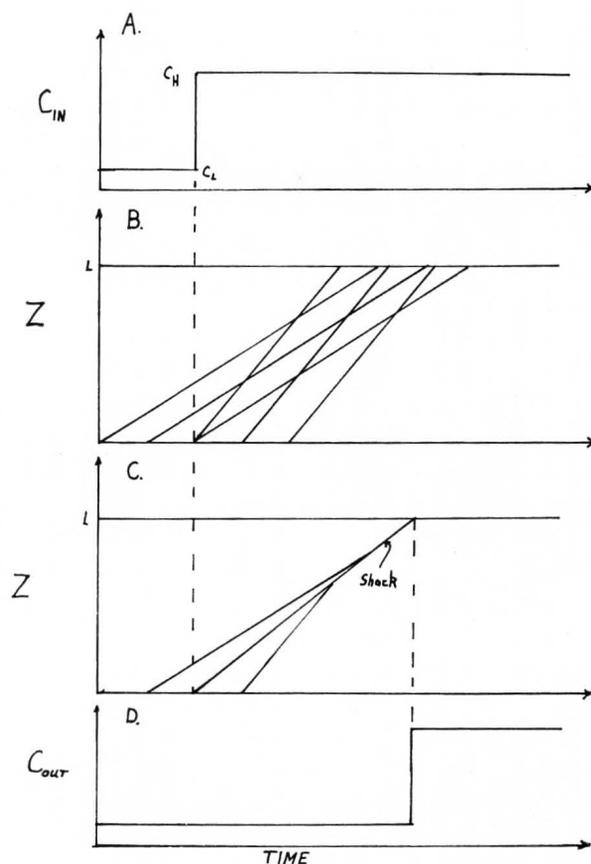


FIGURE 5. Shock wave: A) Inlet concentration; B) Solute waves following Eq. 18; C) Shock wave; D) Outlet concentration.

THE PROCESS DESIGN COURSES AT PENNSYLVANIA:*

Impact Of Process Simulators

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FOR THE PAST 35 years, a two-semester process design sequence has been taught at the University of Pennsylvania. This sequence is unique in several aspects, most notably its diversity of design projects, involving seven faculty advisors and seven consultants from local industry. The fall lecture course, "Introduction to Process Design," covers the methodology of process design and prepares our students for the spring project course, "Plant Design Project," which is intended to provide a meaningful design experience. This article is focused on the impact of process simulators in recent years.

In 1967, we began to introduce computing technology and modern design strategies, principally in the sophomore course on "Material and Energy Balances," and have gradually integrated process simulators into the design sequence. Our objective was to strengthen the highly successful sequence developed by Melvin C. Molstad, A. Norman Hixson, other faculty, and our many industrial consultants. From 1967-1973, our efforts to develop educational materials (principally software) far outweighed the benefits to the students. However, in 1974, the availability of Monsanto's FLOWTRAN Simulator finally made this step successful. Additional industrial simulators have since become available and the benefits to our students now far outweigh our past efforts.

*Based on a lecture at the ASEE Summer School for ChE faculty, Santa Barbara, CA, August, 1982.

Initially, the steps to satisfy a societal need are summarized e.g., the conversion of coal to liquid and gaseous fuels.



Warren D. Seider is Associate Professor of chemical engineering at the University of Pennsylvania. He received his B.S. Degree from the Polytechnic Institute of Brooklyn and Ph.D. Degree from the University of Michigan. Warren's research concentrates on mathematical modelling for process design and analysis. He and his students have developed new methods for calculation of phase and chemical equilibria, analysis of azeotropic distillation towers, analysis of complex reaction systems, and integration of stiff systems. Warren teaches courses with emphasis on process analysis and design. He has co-authored **Introduction to Chemical Engineering and Computer Calculations** (with A. L. Myers) and **FLOWTRAN Simulation—An Introduction** (with J. D. Seader and A. C. Pauls). He helped to organize CACHE and served as the first chairman from 1971-73. In 1979 he was elected Chairman of the CAST Division of AIChE and in 1983 he was elected a Director of AIChE.

Design courses are normally taught last in the chemical engineering curriculum and, hence, the details of the lecture course depend somewhat on the prerequisite courses—and class size. Hopefully, this discussion of our particular format will provide useful ideas.

FALL LECTURE COURSE: INTRODUCTION TO PROCESS DESIGN

The outline of topics and associated lecture hours are listed in Table 1. Two books are required: *Plant Design and Economics for Chemical Engineers* [7], and *FLOWTRAN Simulation—An*

TABLE 1
Outline of topics. Fall lecture course.

	Lecture Hours
Introduction	1
Process Synthesis	1
Analysis of Flowsheets—FLOWTRAN	12
Simulation	
Design of Heat Exchangers	8
Cost Estimation	3
Time-Value of Money, Taxes, Depreciation	3
Profitability Analysis	2
Optimization	3
Heat Integration	4
Synthesis of Separation Processes	2
Selection of Design Projects (for Spring Project Course)	1
Exams	2
	42

Introduction [9]. In addition, materials are taken from seven other sources which are placed on reserve in our library [1, 2, 3, 4, 5, 6, 11].

The course expands upon the steps in the development of a new chemical process as shown in Fig. 1 (based upon a similar figure in Rudd and Watson [8]). Initially, the steps to satisfy a societal need are summarized; e.g., the conversion of coal to liquid and gaseous fuels. Of course, the steps are not always carried out in the sequence shown. For example, a sensitivity analysis is often performed prior to an economic analysis. In the integrated plants of today, aspects of transient and safety analysis must also be considered in the synthesis of the process flowsheet.

Next, the steps in the synthesis of a vinyl chloride process are illustrated with the intent of exposing the steps that enter into the invention of alternative flowsheets. Fig. 2 shows the evolution of one flowsheet, beginning with selection of the reaction path (not shown), followed by the distribution of chemicals (matching sources and sinks and introducing recycle), selection of the separation steps, the temperature and phase change operations (not shown), and, finally, the integration into chemical process equipment. This is based upon Chapter 3, "Process Synthesis," in *Introduction to Chemical Engineering and Computer Calculations* [6]. It is noteworthy that steam is used to vaporize dichloroethane and cooling water to cool the reaction products in a quench operation. We emphasize the desirability of heat integration, when feasible, but because carbon would deposit in the evaporator tubes, a rapid low-temperature quench, with water as the cool-

Principal emphasis is given to the subroutines to model the process units such as vapor-liquid separators, multi-staged towers, heat exchangers, compressors, and reactors.

ing medium, is necessary.

Having introduced the concepts of flowsheet synthesis, attention is turned to the analysis of alternative flowsheets. In practice, of course, the two go hand-in-hand. FLOWTRAN is used principally because our book [9] is written in a tutorial fashion, as compared with the usual User Manuals. FLOWTRAN has been available for students on United Computing Systems, but its usage has been limited by the relatively high cost of commercial computers. Recently, however, like ChemShare (DESIGN/2000) and Simulation Sciences (PROCESS), Monsanto has made FLOWTRAN available for installation on university computers—

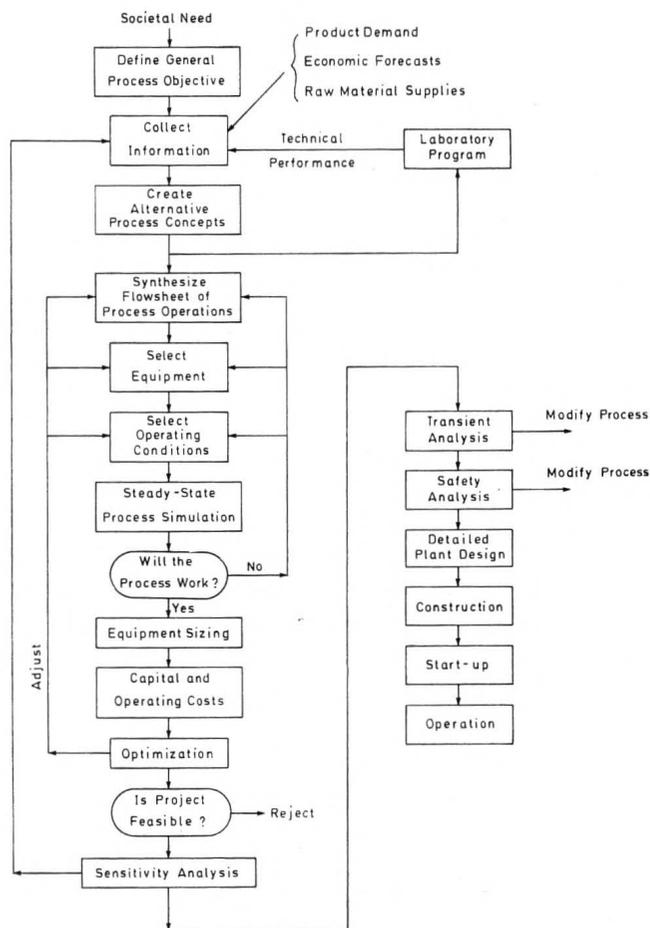


FIGURE 1. Steps in the development of a new chemical process.

greatly improving the effectiveness of process simulators in the design course.

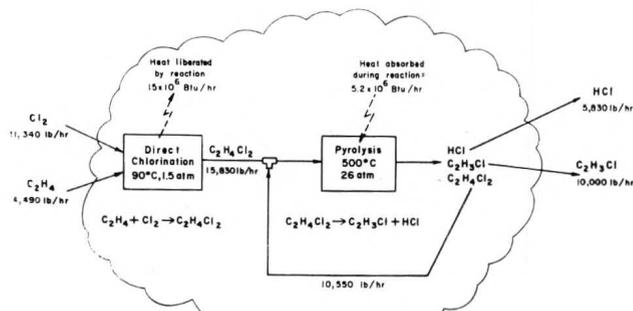
Principal emphasis is given to the subroutines to model the process units such as vapor-liquid separators, multi-staged towers, heat exchangers, compressors, and reactors. There are several subroutines to solve the equations that model each process unit. The models vary in specifications and rigor and it is important that the design student understand the underlying assumptions, but not the solution algorithm. We review the assumptions and make recommendations concerning usage of the subroutines listed in Fig. 3. For example, the PUMP routine disregards the capacity-head curve and uses the viscosity of *pure water*. When designing a distillation tower, use of DSTWU is recommended to calculate the minimum number of trays, the minimum reflux ratio, and the theoretical number of trays (given the reflux ratio), followed by DISTL which uses the Edmister assumptions to simulate the tower and, in some cases, FRAKB or AFRAC to solve the MESH equations with fewer assumptions.

The synthesis of the simulation flowsheet is also emphasized with consideration of novel ways of using the subroutines to analyze a process flowsheet. For example, consider the quench process (Fig. 4a) in which hot gases are contacted with a cold liquid stream. Given the recycle fraction, and assuming that the vapor and liquid products are at equilibrium with no entrainment, most designers would develop the simulation flowsheet shown in Fig. 4b. However, iterative recycle calculations are unnecessary because the vapor and liquid products (S3, S5) are independent of the recirculation rate. In a more efficient simulation flowsheet, the IFLSH subroutine determines the flow rate and compositions of S3 and S5 (see Fig. 4c). Then, MULPY subroutines compute the flow rates for S4 and S6. Most students use the "brute-force" approach in Fig. 4b, requiring about 5-10 iterations with Wegstein's method, before we demonstrate that the iterative recycle calculations can be avoided.

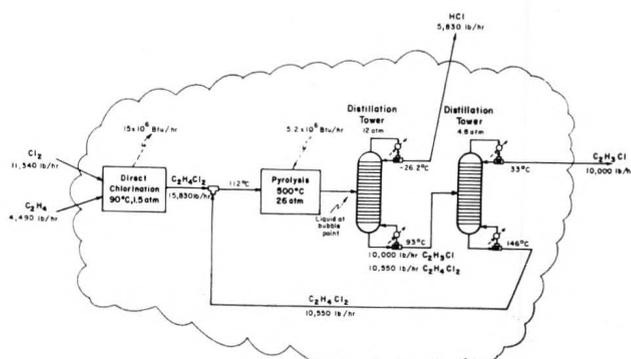
These lessons are reinforced with a problem to simulate the reactor section of the toluene hydrodealkylation process [9, p. 228]. Feed toluene is mixed with recycle toluene and a recycle gas stream. The reaction products at 1268°F are quenched and the recycle fraction is adjusted to reduce the product temperature to 1150°F. As above, the iterative recycle calculations can be avoided, although most students use the brute-



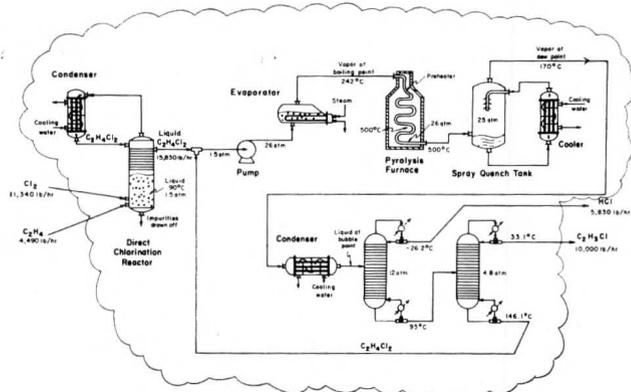
a) The process synthesis problem



b) Flow sheet showing distribution of chemicals for thermal cracking of dichloroethane from chlorination of ethylene (reaction past 3)



c) Flow sheet showing separation scheme for vinyl chloride process



d) Flow sheet showing task integration for the vinyl chloride process

FIGURE 2. Synthesis of a vinyl chloride process (Myers and Seider [6]).

force approach.

The FLOWTRAN subroutine EXCH1 implements the method of thermodynamic effectiveness (computes terminal temperatures, given the area and overall heat transfer coefficient), and the EXCH3 subroutine implements the log-mean temperature difference method (computes the area, given terminal temperatures and overall heat transfer coefficient). Since these methods are not covered in our course on heat and mass transfer, the methods are derived and problems are worked using Chapter 11 of *Principles of Heat Transfer* [5] as text material. Then, the students design a heat exchanger (e.g., 1-4 parallel-counterflow) with correlations for the heat transfer coefficients and pressure drops on the shell and tube sides and the methods presented by Kern [4] and Peters and Timmerhaus [7]. This exposes the student to more detailed analysis procedures than are available in most process simulators. Such detail is recommended only when the approximate models introduce large errors and the cost of a heat exchanger contributes significantly to the economics of the process.

This leads to methods of cost estimation. FLOWTRAN has subroutines for cost estimation, but the assumptions of the cost models are not

FIGURE 3
FLOWTRAN subroutines (blocks)

Flash	IFLASH	Isothermal flash
	AFLASH	Adiabatic flash
	BFLASH	General purpose flash
Stagewise separation	SEPR	Split fraction specification
	DSTWU	Winn-Underwood-Gilliland distillation
	DISTL	Edmister distillation
	FRAKB	Tray-to-tray distillation (KB method)
	AFRAC	Tray-to-tray distillation and absorption (matrix method)
Heat exchange	HEATR	Heat requirement
	EXCH1	Shell and tube—method of thermodynamic effectiveness
	EXCH3	Shell and tube—log-mean temp. diff. method
Reactor	REACT	Fractional conversion specification
	XTNT	Extent of reaction specification
Compression	PUMP	Centrifugal pump
	GCOMP	Compressor (or turbine)
Misc.	ADD	Mixer
	SPLIT	Stream splitter
	MULPY	Stream multiplier

stated or referenced. Since no basis is available for justifying their results, well-established and clearly stated methods are preferred. The factored cost methods of Guthrie [3] have been used to date, but the factors in his article need updating. We are evaluating the PCOST program developed at Purdue University [10] and the data

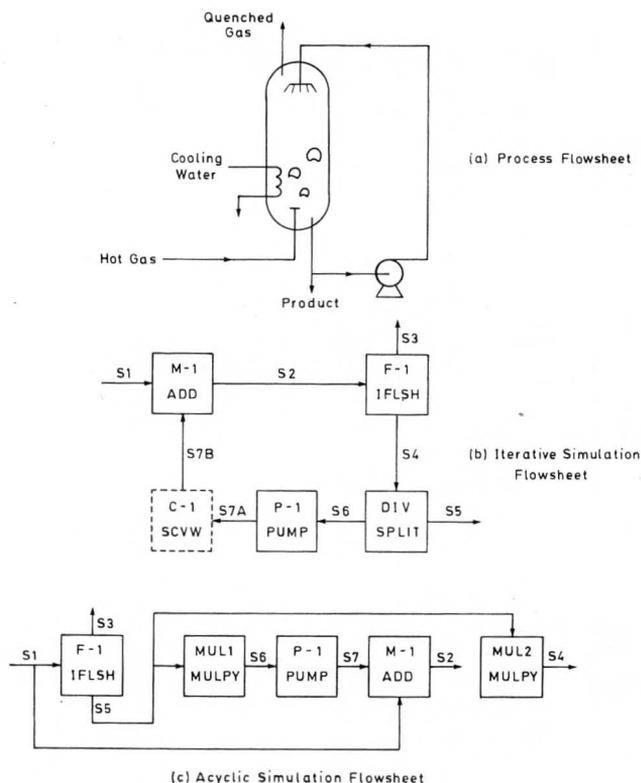


FIGURE 4. QUENCH process.

books of Woods [12]. Both give cost curves and factors based upon more recent cost data.

For production or operating costs, the recommendations of Peters and Timmerhaus in Chap. 5 are used with concentration on the direct production costs, such as for raw materials, operating labor, and utilities. The Chemical Marketing Reporter provides the costs of chemicals bi-weekly (often for several locations within the United States).

Next, the concepts of profitability analysis are introduced, following the sequence of Peters and Timmerhaus in Chaps. 6-9. The concepts of simple and compound interest are applied to give the present and future values of an investment and to define an annuity. Then, capitalized costs are covered to provide a basis for evaluating the cost of equipment having different service lives. For

Continued on page 41.

INTRODUCING THE REGULATORY PROCESS INTO THE CHEMICAL ENGINEERING CURRICULUM *A Painless Method*

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ENGINEERING FACULTY CAN NO longer doubt that government regulations have had a major impact on engineering practice. Public policy decisions have resulted from social concerns and have mandated engineering solutions in many areas, such as environmental pollution, proper disposal of hazardous wastes, consumer product safety, and the control of exposure to carcinogenic and toxic materials. Because technological invention has such a great impact on our society, the scope of an engineer's responsibilities must include a sensitivity for social concerns and the participation in public policy issues involving technology. Engineers are directly affected because our designs are often covered by government regulations. Engineers must also provide the data and technical judgment needed to formulate public policy and to write realistic and technically feasible regulations to implement the policies. If all these things are true, then an argument can be made that engineering students should be exposed to the interaction of engineering and public policy as part of their professional education.

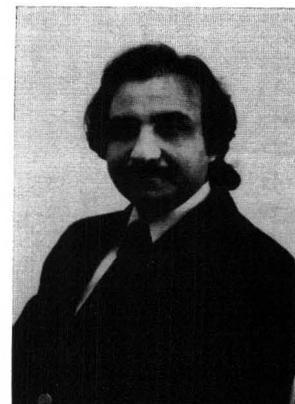
There are at least three different ways that an introduction to government regulations and the

Engineers are directly affected because our designs are often covered by government regulations. Engineers must also provide the data and technical judgment needed to formulate public policy. . .

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regulatory process can be integrated into the chemical engineering curriculum. The first approach would be to recommend an elective course on the topic. Many universities have introduced "Society and Technology" elective courses which usually focus on the impact of technology as a social phenomenon, rather than on the technical aspects of public policy issues. These courses are often not recommended by engineering faculty because they do not meet the requirements as a

technical or a social science elective. Generally these courses are not taught by engineering faculty. Thus, engineering students are deprived of a role model and get the feeling that engineers are not concerned with the regulatory process and public policy issues. Also, since the courses are elective courses, many students may not select them voluntarily.

A second approach is the use of interdisciplinary project-oriented courses. The course would be team-taught by both engineering and social science faculty and the students could be both technical and non-technical. As an example, a course could be devoted to a project of cleaning up a river where the team would have to consider both the technical and the social aspects of different solutions. These courses require a considerable amount of faculty time to organize and develop. They also require cooperation of different departments operating on different budgets.

A third technique is to use engineering case studies to introduce public policy considerations directly into the engineering curriculum. The use of case studies can overcome the local problem of developing and sustaining projects with public policy issues. If case materials were available and if only part of a course involved issues concerning public policy, then many faculty might be willing to get involved. On the other hand, few engineering faculty would feel comfortable with or be willing to teach an entire course dealing with public policy. However, if faculty would give students even a small peek at public policy issues they should be able to foster an awareness of the relevance of the social science/humanities component in education. We, as engineering faculty, might even grow a bit as we come to understand the impact of policy issues on the practice of engineering education.

We would like to describe a project which was aimed at developing a number of case studies with public policy considerations and how we have introduced public policy into our undergraduate curriculum at Howard University. We would also invite you to get involved so that case studies can be developed that can be used in chemical engineering curricula.

THE EPEPP PROJECT

The Educating Prospective Engineers for Public Policy (EPEPP) project is administered by ASEE with the University of Washington as the academic sponsor and Professor Barry Hyman [2]

The goal of the project is to provide future engineers with the tools necessary to contribute professionally to the resolution of technically intensive public policy issues.

as the project director. The project has the financial support from the National Science Foundation, Sun Oil Company, General Motors, and nine engineering societies. AIChE has become a sponsor for the 1984 program.

The goal of the project is to provide future engineers with the tools necessary to contribute professionally to the resolution of technically intensive public policy issues. The project is in response to the needs of society to have a greater technical input into the making of public policy in engineering and technology areas and to the needs of engineers to have a broadened awareness and understanding of the meaning of public policy. The project is geared to produce case studies on topics concerning public policy issues which have technical components. The objective of the project will be accomplished by the direct experience of a small number of students and faculty and by the integration of the case studies into the typical engineering curriculum.

The project has three major integrated components: 1) Washington Internship for Students of Engineering (WISE); 2) the development of case studies on engineering and public policy on topics based on the WISE program; and 3) a series of regional ASEE faculty workshops to promote the utilization of case studies.

The WISE Program provides an opportunity for about 15 third-year engineering students to spend 10 weeks during the summer studying the relationship between engineering and public policy. An objective of the WISE program is for the students to gain an understanding of the operation of the federal government so that they can appreciate the non-technical aspects of technology related public policy problems. The students receive a stipend of \$1750 to cover expenses. They also receive 3 credits from University of Washington. Their goal for the summer is to complete a written report on their project to provide the basis of a case study. The students are selected competitively by the sponsoring engineering societies. Fortunately, five chemical engineers have been selected even though AIChE was not a sponsor.

TABLE 1
WISE Participants*

INTERNS	1980	1981	1982
Mechanical Engineering	5	4	5
Civil Engineering	3	2	3
Chemical Engineering	2 (SAE, NSPE)	2(ANS)	1(ANS)
Electrical Engineering	1	2	1
Agricultural Engineering	2	1	1
Industrial Engineering	0	1	2
Aeronautical Engineering	0	1	0
Manufacturing Engineering	0	1	0
Energy Systems Engineering	0	1	0
Nuclear Engineering	1	0	1
Engineering & Public Policy	1	0	0
Engineering Science	0	0	1

*One or more students were sponsored by the societies shown in parenthesis—Society of Automotive Engineers (SAE), National Society of Professional Engineers (NSPE) and American Nuclear Society (ANS).

Table 1 lists past WISE participants by background.

In pursuing their specific projects, the students spend about 5 hours a week in a classroom setting discussing the dimensions of engineering and public policy [4]. In pursuing their specific projects, the students interact regularly with ASEE headquarters, the Washington office of their sponsoring societies, government agencies, congressional staff, corporate lobbyists and consumer advocates. They also attend seminars by leading experts on current issues of interest to the technical community and to society.

The classroom work and field work is coordinated by a faculty-member-in-residence. The faculty-member-in-residence meets regularly with individual WISE students to monitor the progress of their activities. The faculty-member-in-residence is selected on the basis of first-hand experience with public issues, record of teaching, and familiarity with the case method of instruction. Professors Charles Overby (Ohio University), Paul Craig (UC-Davis), and F. Karl Willenbrock

TABLE 2
1980 WISE Case Studies

- Regulation of trihalomethanes in drinking water
- Subsurface disposal of hazardous waste
- Problems with implementing an effective automobile fuel economy program
- Management of high-level radioactive wastes
- Building energy performance standards

(SMU) were the faculty-members-in-residence for the first three years of the program.

The second phase of the EPEPP project is to convert the student papers into draft cases and to coordinate the preparation for classroom testing of the drafts [1]. In autumn 1980, in response to a national questionnaire, about 75 faculty expressed interest in using a case on a specific area and to participate in workshops on the use of the cases. On the basis of the questionnaire, five topics were selected by the project director to be converted into draft cases. The topics selected are listed in Table 2. As part of the process of converting the papers into draft cases, additional introductory material was written describing the regulatory process. Exerpts from the *Federal Register* and transcripts of expert testimony on proposed rules were included where appropriate. An *Instructor's Guide* was also written for each case. The *Guide* contains suggestions on how each case might be used.

The third and final component of the project is the validation of the cases and their integration into engineering curricula. The validation and integration of the cases are to be accomplished by classroom testing and a series of workshops at

TABLE 3
Faculty Participation

DISCIPLINE	NUMBER
C.E.	3
Ch.E. (Howard, Suny-Buffalo)	2
M.E.	2
I.E.	2
E.E.	1

regional ASEE conferences. The workshops are to encourage and publicize the use of EPEPP cases on many campuses. Ten of the faculty that expressed an interest in the project were invited to participate in a case workshop which was held in conjunction with the 1981 ASEE Annual Conference. The field test faculty were selected to get a mix of disciplines and geographical areas. The distribution by disciplines is shown in Table 3.

USING ENGINEERING CASE STUDIES

An engineering case study is a written account of an engineering activity as it actually took place [3]. A case gives the sequence of events of a real experience, often from the viewpoint of one or more participants. Unlike a technical paper

which focuses on the validity of a solution, a case considers how the results were obtained. A case often shows how the participants interacted to accomplish the engineering task. A case is often written in segments to allow class study or discussion at critical decision points. Cases, like design projects, have no single correct answer and depend on many subdivisions of engineering. They often raise questions of human behavior and ethics as well as technical questions, and thus permit many possible solutions.

Engineering cases can be used in many different ways. A list of some of the more common methods is given in Table 4. Using cases as read-

TABLE 4
Classroom Uses of Case Material

- Reading assignments
- Background to specific problems
- Practice in formulating problems
- Subjects for class discussion
- Medium for relating engineering history and illustrating the engineering method
- Motivation for laboratory work
- Background and source for research or design projects

ing material is the simplest method, but it is probably the least effective. One of the other methods should probably be selected since students will be more involved in the learning process.

EXPERIENCE AT HOWARD UNIVERSITY

We used the draft case study "Regulation of Trihalomethanes (THM's) in Drinking Water" as part of our first chemical engineering course "Introduction to Engineering Design." All of our students were concurrently taking their second semester of chemistry and calculus. The THM case was selected from the available cases because it had a strong chemistry component and the topic had the most interest to chemical engineers.

The students were all given a copy of the case study as a reading assignment and were given a short technical presentation on the formation of THM's in water. Every attempt was made to insure unbiased dissemination of information. The students were next organized, voluntarily, into one of six groups consisting of the EPA, Congress, industry, consumer groups, research centers and universities, and judges. Each group was asked to prepare themselves for a role-playing discussion of the topic. Each group then met individual-

Unlike a technical paper which focuses on the validity of a solution, a case considers how the results were obtained . . . Cases, like design projects, have no single correct answer and depend on many subdivisions of engineering.

ly to formulate their strategy. They were encouraged to explore the topic in as great technical detail as possible. The students were expected to present and defend the positions of their group, rather than express their personal views.

The discussion period consisted of a two-hour session which began by having each group's spokesperson summarize the group's role in the regulation process. Two faculty members and a senior student joined the judges group to moderate and guide the discussion and to bring out various aspects of the problem. The judges also acted to evaluate individual student and group performance. A lively debate followed, with each group questioning the others. The judges were successful in keeping the discussion going and getting most of the students involved in the discussion. The student judges were unanimous in siding with the consumer group, their evaluation being more on an emotional basis than a factual one. The faculty judges felt that the discussions should have been more technical, but everyone agreed that they had a better understanding of the regulatory process and why engineers must be involved.

We plan to continue using the case studies in our freshman class and intend to introduce them in the senior level design course. We expect to get a better technical response from the seniors, but both groups will gain a sensitivity for the social responsibility of engineers. □

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MODULAR INSTRUCTION UNDER RESTRICTED CONDITIONS

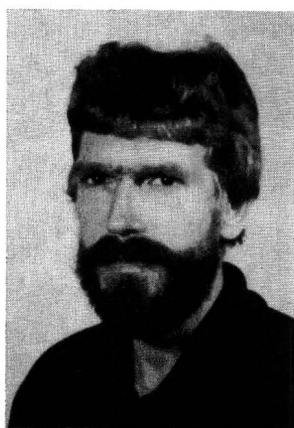
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DUE TO THE ECONOMIC recession and cuts in educational budgets, discussions on the efficiency of the education system (especially with regard to faculty time) have only recently been started in the Western world. For developing countries, however, this is not only a well known problem but only one of many problems. Besides having a



Tjipto Utomo graduated from high school in 1941 but had to suspend his academic activities during the second World War and the following struggle for independence. He began university studies in 1950 and graduated from the chemical engineering department of the Institute of Technology Bandung in 1957. He obtained his MChE degree in 1959 from the University of Louisville and is presently a professor at the Institute of Technology Bandung. (L)

Kees T. A. Ruijter is a graduate in chemistry from the University of Amsterdam. During the years of 1979-1983 he worked in the Dutch-Indonesian program on upgrading chemical engineering education in Indonesia. Before that he was with the Twente University of Technology (Holland) working on the development of chemical engineering education and he has now returned there. His main areas of interest are lab course improvement, efficiency of the learning-teaching process, and curriculum evaluation and development. (R)

small faculty, underpaid and overoccupied with additional activities, universities often face such conditions as inhomogeneous classes (in capability as well as in motivation), low staff-student ratios, rapidly increasing enrollments, and the need for more graduates.

In a cooperative project between the Bandung Institute of Technology (ITB) and technical universities in The Netherlands, the educational system was improved gradually within these restrictive conditions [1]. One of the main features, a modified modular instructional system, is the subject of this article.

THE TRANSPORT PHENOMENA COURSE

The transport phenomena (T.P.) course is a fourth semester course. However, because the first year is a common basic science program for all ITB students, it is their first real confrontation with engineering concepts. For this reason and because less than 30% of the students passed yearly, the T.P. course was chosen as our pilot course.

In the first phase of reconstruction the course and its context were thoroughly evaluated. Some measures were investigated in an experimental set-up and implemented step-wise. The main findings were

1. Only a few students perform at an acceptable level. Many students know the principles and laws but cannot apply them in any situation.

We decided to restrict the number of topics to be discussed and to require the students to perform at a higher level of competence.

2. The individual differences in student performance are enormous (despite the common first year program).

To minimize this problem we developed a modular instruction scheme enabling the students to study at their own pace.

3. The students (80%) are not able to read English texts.

Also, because the lecture as a source of informa-

tion is inadequate for an inhomogeneous class, we decided that all information (text, examples, exercises and solutions) should be made available on paper.

- Students do not solve the problems systematically and they have difficulty in describing physical phenomena in mathematical terms.

For this we adopted a methodology for solving science problems and modified it for the T.P. problems [2, 3].

- Individual guidance of students working on problems is quite effective but cannot be applied to exercises at home because of lack of tutors.

An instructional scheme was developed wherein the presentation of theory and applications by the teacher was followed directly by individual exercises in class and continued at home.

- The usual norm-referenced grading procedure appears to be inadequate to evaluate effectiveness of learning and instruction and is demotivating for the students.

In grading the module exams we applied the criterion-referenced performance assessment. As criterion we chose 60%, the minimum level of mastery necessary to take the following module.

MODULAR INSTRUCTION

Modularization is a classical solution for the problem of an inhomogeneous student population. Students in such a group differ in capability, intelligence, and motivation, resulting in different time requirements for study. In a modular scheme the allowed time is made to correspond with the students' required time. The course is divided into modules, enabling students to choose more or less individual paths [4]. However, we could not apply all principles of modular instruction because

- ITB students are not able to study on their own (they have never studied in instructional schemes other than the lecture).
- Faculty time is very restricted and assistants, proctors, or administrative staff are not available.

Therefore we limited the number of examinations and the opportunity for remedial instruction and developed a teacher-paced modular system. The contents of the T.P. course are very suitable for modularization because of the similarity among the three sections: transfer of momentum, heat, and mass. After the first part the other two can be presented by analogy.

The contents were divided into 6 modules; 3 modules covering the basics of momentum, heat, and mass transfer; 2 covering extensions and applications of these; and the 6th module (C-2, extension of mass transfer) is postponed to the unit operations courses. The first module is a small module, to encourage the students to start their

We developed a teacher-paced modular system which allows the students to study on a full or a 60% pace (a 2 gear-system).

study immediately. The students can concentrate on the macro-balance approach and by the time they are acquainted with this concept and the new instructional system, the micro-balance approach is introduced (see Table 1).

TABLE 1
Contents of 5 Modules

MODULE	SUBJECT
A-1	INTRODUCTION
	Transport phenomena
	Laws of conservation
	MOMENTUM TRANSPORT
	Laminar flow
	Sample problems
	Abstract and exercise
	Dimensional analysis
	Exercise
	A-2
Turbulent flow	
Pressure drop in tube flow	
Flow in conduits with varying cross section	
Sample problems	
Abstract and exercise	
B-1	MICROBALANCES
	Introduction
	Equation of Continuity
	Equation of Motion
	Application of the equation
	Abstract and exercise
	HEAT TRANSPORT
	Introduction
	Equation of Energy
	Application of the equation of energy
Abstract and exercise	
B-2	Unsteady state conduction
	Heat transfer by convection
	Radiation
	Abstract and exercise
C-1	MASS TRANSPORT
	Diffusion
	Mass transfer
	Coefficient of mass transfer
	The film theory
	Concentration distribution
	Unsteady state diffusion
	Mass transfer by convection
	Simultaneous heat and mass transfer
Abstract and exercise	

The examination procedure forces the students to concentrate on the basic modules. Only students who pass the first module (A-1) are allowed to proceed to the second module (A-2). The others must repeat the A-1 exam, which is scheduled at the same time as the regular module A-2 exam. This procedure requires the least possible time from the lecturer. For the same reason, no remedial instruction for repeating students is organized. The printed text and work-out exercises should enable them to prepare for the repetition. As a consequence, as many students as possible who are starting to study heat transfer have passed module A-1 and have a proper comprehension of the essentials of momentum transfer. The procedure for the second section is quite similar.

A calculation showed that the examination for modular instruction should consume no more instructor time than examination by the former method, if 60% of the group passes on the first attempt.

Since 1981 all homework problems have been directly related to classroom exercise. Feedback on the exercises was provided in class and in the lecture notes (answers), while many worked-out problems were shown in show-windows. All problems were worked out in four phases: analysis, plan, elaboration, evaluation. Only a precise result in one phase allows the problem solver to proceed to the next phase. The results at each phase enable the instructor to provide adequate feedback and allows the students to look for adequate information about their solving process. This problem solving scheme was also followed for examinations.

RESULTS

The module test results of 1981 are shown in Table 2. The student performances were acceptable except for modules B-2 and C. Here a final module effect, "we have got the ticket," seems likely.

After the tests only 66% had to repeat two modules or less. Most of them were able to pass the respective parts of the final exam and thus the whole course. This and the overall effect of the reconstruction is shown in Table 3.

By means of questionnaires, interviews, and analysis of examination results, other information was collected on

- **TIME SPENT** Students did not feel the modular

TABLE 2
1981 Module Test Results

MODULE	STUDENTS WITH SCORE ABOVE 60%			% Students passed (N=135)
	First attempt	Second attempt	Final exam	
A-1	95 (70%)	34	1	96
A-2	67 (70%)*	**	35	67
B-1	97 (72%)	26	1	92
B-2	55 (57%)	**	1	41
C	27 (20%)	**	77	77

*Percentage of number of participants in the examination. Here 67 passed out of 95 students allowed to participate.

**For these modules the final exam is the second attempt.

system forced them to spend more time on transport phenomena.

- **PROBLEM SOLVING** The plan phase was very difficult for the students. The lecturer considers the systematical method on problem solving not only as a means for learning but also as a sound tool for instruction and explanation to the students.
- **ATTENDANCE AT LECTURES/INSTRUCTIONS** The number of students attending the lectures during the semester was higher than before. The decrease in attendance during modules B-2 and C was partly caused by the interference of laboratory activities. This explains the lower scores on these modules.
- **ACCEPTANCE** Students and lecturer were very positive about the reconstructed course and the modular system.

CONCLUSIONS

The examination results of the reconstructed courses and the general acceptance show that the modular T.P. course is a substantially improved course. The better performance of the students is not a result of an increase in their efforts or the

TABLE 3
Distribution of Final Grades for the TP Course During and After 1980

GRADE	1980	1981	1982
A	0%	3.3%	21.0%
B	2.5%	30.1%	29.5%
C	18.5%	46.3%	27.6%
(A+B+C)	(21.0%)	(79.7%)	(78.1%)
D	25.2%	12.2%	5.7%
E	30.3%	0%	4.8%
F	23.5%	8.1%	11.4%

A/B/C—Passed: D—Passed conditionally: E/F—Failed.

activities of the teacher, but by a more efficient use of the students' and lecturer's time; i.e. the internal efficiency of the instructional process has been improved.

The main feature of the new course is the modular system. We developed a teacher-paced modular system which allows the students to study on a full or a 60% pace (a 2 gear-system). Remedial teaching was not applied. This system resulted in a constant study load in transport phenomena during the semester and few students lost the junction in an early phase as they had in the past. We may conclude that it is worthwhile to apply a modular scheme, even under very restricted conditions of faculty time. □

ACKNOWLEDGMENT

This educational upgrading program was sponsored by The Netherlands Ministry of Development Cooperation.

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ChE book reviews

THE HISTORY OF CHEMICAL ENGINEERING AT CARNEGIE-MELLON UNIVERSITY

*By Robert R. Rothfus
Carnegie-Mellon University,
Pittsburgh, PA 15213, 302 pages*

**Reviewed by
Robert B. Beckmann
University of Maryland**

The author, Robert R. Rothfus has been associated with the chemical engineering program at Carnegie-Mellon, as a graduate student and faculty member, for over forty years, a period that covers over half the Chemical Engineering programs total existence and almost the entire period of its existence as a separate department. The book was obviously a labor of love to Professor Rothfus

as evidenced by its attention to statistical detail and anecdotes as well as historical development.

The first part of the book outlines the historical development of the school beginning with Andrew Carnegie's original offer to establish an institution for technical education on 15 November 1900 and traces the development from the "Carnegie Technical Schools" to the transition (1912) to Carnegie Institute of Technology and the final transition (1967) to Carnegie Mellon University. Following the detailed development to University status the book turns to the historical growth and development of the original School of Applied Science . . . one of the four original Schools founded by the Carnegie gift . . . to the current College of Engineering. The first diplomas in Chemical Engineering Practice were awarded in 1908 along with the initial "Diplomas" in the Civil, Electrical, Mechanical and Metallurgical Practice fields. Included are statistical and organizational details relating to the various departments, research laboratories, interdisciplinary programs, the academic calendar, tuition and enrollments.

The development and growth of the Chemical Engineering Department is chronicled in Chapter 4, beginning with the original Chemical Practice program in 1905 and the transition to Chemical Engineering in 1910. The chapter divides the history of the Department into quantum periods depending upon who was the chief administrative officer of the department during that period. The problems, issues and accomplishments of each period are well chronicled. The development is carried through 1980.

Part Two of the book, which comprises over 40 percent of the total pages is devoted to an exhaustive presentation of departmental statistics from its inception through 1980. The various chapters include such topics as enrollment and degrees granted, the faculty over the years, the changing undergraduate curriculum and graduate instruction, research activities and financial support and anecdotal sections devoted to departmental "personalities" and a recalling of the unusual, comical and tragicomical events over the years. The Appendices, about a third of the book, are devoted to a complete delineation of faculty, staff and students (graduate and undergraduate) by name and years of service, or graduation, who have been a part of the Carnegie Story in chemical engineering.

Continued on page 48.

The object of this column is to enhance our readers' collection of interesting and novel problems in Chemical Engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class or in a new light or that can be assigned as a novel home problem are requested as well as those that are more traditional in nature that elucidate difficult concepts. Please submit them to Professor H. Scot Fogler, ChE department, University of Michigan, Ann Arbor, MI 48109.

SETTING THE PRESSURE AT WHICH TO CONDUCT A DISTILLATION

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This memorandum was issued to the students in chemical engineering stage operations, most of whom are sophomores and first semester juniors but none of whom have yet had any heat transfer courses. Thus the elementary explanation of heat exchangers may be unnecessary for more experienced students.

The subject of the memorandum is usually not covered at all in stage operation texts, or at most only lightly covered. In most of the problems on this subject for distillation the pressure is given but there is no statement as to how it is determined.

When the pressure is given, most students (and a few professors) will have no idea whether it is reasonable or even possible.

THE MINIMUM PRESSURE at which to conduct a distillation is set by the condenser. The temperature of condensation of the top product must be high enough to condense it with the cooling water available. We remove heat in the condenser with cooling water which rises in temperature as it removes heat, since its sensible heat rises

The maximum pressure for the separation is set by the reboiler. The boiling temperature of the bottom product must be low enough to be boiled by condensing the steam available.

with temperature. Also the condensing temperatures of the overhead product increase with increasing pressure.

The maximum pressure for the separation is set by the reboiler. The boiling temperature of the bottom product must be low enough to be boiled by condensing the steam available. We must be able to add heat to the reboiler, by having the heat source at a higher temperature than the bubble point of the bottom product.

HEAT EXCHANGERS

Both the condenser and the reboiler are generic heat exchangers and all heat exchangers require that there be a temperature difference between the source of heat and the sink, *i.e.* the source must be hotter than the sink. The local temperature difference (Δt) between the two streams exchanging heat is often not a constant but it must be everywhere greater than zero. If the Δt is zero anywhere in the exchanger, the area required to transfer the heat becomes uneconomically large. It is useful to plot the temperature history in any heat exchanger to see what the Δt (driving force) is and how it varies throughout the device. For example, the overhead vapors (from a distillation column when heat is removed) will first begin to condense at their dew point. Further cooling will condense more until it is completely condensed at the bubble point.

THE CONDENSER

If the dew point of the overhead product at the column pressure is 140°F and the bubble point is 120°F—and if the inlet cooling water is

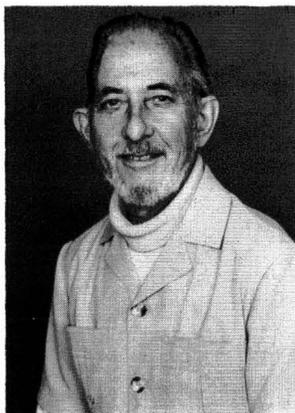
70°F and a 30°F rise may be taken—the temperature pattern in the condenser when the overhead is condensed completely but not subcooled is represented in Fig. 1.

The Δt driving heat transfer is thus between 40° and 50°F. This is quite adequate, but Δt 's as low as 10 or 20°F are not uncommon.

Now if the pressure of operation were lowered then the dew and bubble point temperatures would be less than those shown and they might approach the cooling water temperature, thus decreasing the Δt which drives heat transfer and increasing the area required according to the design equation

$$A = \text{ft}^2 \text{ Area req'd.} = \frac{Q}{U \Delta t_{\text{mean}}}$$

where Q = the rate at which heat is to be transferred (Btu/hr.)
 U = the overall heat transfer coefficient Btu/[(hr) (ft²) (°F)]
 Δt_{mean} = the mean driving force temperature difference in °F.



All during my undergraduate days (1936-1940) at the University of Washington in Seattle, the country was in the depths of the great depression and jobs were scarce. After obtaining my M.S. I was lucky to get one job offer with an oil refinery in California which I promptly accepted and started to work 24 November, 1941 just two weeks before Pearl Harbor.

The refinery work was very good chemical engineering experience for me. I worked there for over 7 years and remember wondering when I first arrived, why all de-butanizers operated at 50 to 60 psig and all depropanizers operated at 180 psig. When I later figured it out it was simple but I seldom come across any professors who have thought about it enough to have a well organized answer to my question of "How is the Pressure Set for a Distillation Column?" I have yet to see a thorough or even a sketchy treatment of this subject in any text on distillation. So I thought it would be appropriate to write this article for a class in Stage Operations and perhaps to publish it in *CEE*. The elementary discussion of heat exchangers was necessary because the students had not yet taken a course in heat transfer. (Informal biographical sketch submitted by author.)

The condenser thus sets the minimum pressure at which the column must operate. To find this minimum pressure, first find the bubble point pressure of the D product . . .

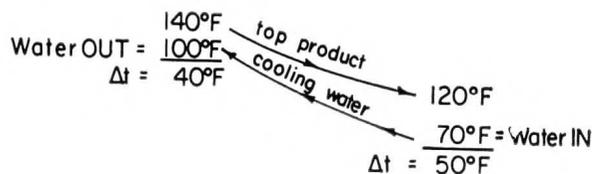


FIGURE 1.

The mean Δt is usually somewhere between the two terminal temperature differences (unless one of them is 0) and you will learn in Transport II how to calculate these mean Δt 's.

The condenser thus sets the minimum pressure at which the column must operate. To find this minimum pressure, first find the bubble point pressure of the D product at a temperature of say 10° or 20°F higher than the inlet cooling water temperature. For a binary distillation this can be taken from the P-x-y diagram for that temperature, and for multicomponent mixtures one must use the relations for vapor-liquid equilibrium in multicomponent mixtures.

THE REBOILER

As the column pressure is increased, the Δt in the condenser will just get bigger and this is satisfactory; but the pressure also affects the operation of the reboiler in the opposite fashion. The material being boiled in the reboiler has the composition of the bottom product and the boiling temperature is the bubble point of W, the bottom product. It is fixed once its composition and the pressure are known. The heat source is usually condensing steam and the steam condensing temperature must thus be at least 10 or 20°F above the bubble point of the bottoms product. Since the latter temperature goes up with increasing pressure, this sets a maximum pressure at which the distillation may be conducted. The temperature pattern in the reboiler is simpler than that in the condenser since neither the steam nor the bottom product changes temperature as heat is transferred. If, for example, the bubble point of W is 300°F at the column pressure, and we have steam available at 300 psig, the condensing temperature for this steam (steam tables) is

about 422°F. This temperature pattern is illustrated in Fig. 2.

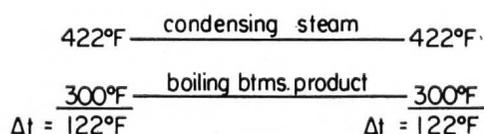


FIGURE 2.

The bubble point of the bottom product (which increases as P goes up) and the available steam pressure (and its condensing temperature) thus set a maximum pressure for the distillation. To find this pressure, estimate the bubble point pressure of the W product at a temperature of say 20°F (more or less) below the condensing steam temperature.

We now have both a maximum and minimum pressure at which the distillation can be carried out. Some pressure between these two would be used in the final design and its optimum value will be determined by an economic balance. The items to consider in such an economic balance are:

1. The effect of P on the temperatures of condensation of the overhead and on the boiling temperature of the bottom product which affect the mean Δt in the condenser and reboiler and thus their areas. Each of these exchangers may be made smaller at the expense of the other one by adjusting the pressure up or down between the limits imposed. The higher the pressure, the smaller the condenser and the larger the reboiler, and vice versa. Pressure affects these two exchangers in opposite directions because we are removing heat from one and adding heat to the other.
2. The effect of the column design pressure on its wall thickness and thus cost.
3. The effect of pressure on the vapor-liquid equilibrium. This effect is likely small for nearly ideal liquid solutions since for these liquid mixtures the relative volatility is independent of pressure. For hydrocarbon systems for example, by changing the absolute pressure by a factor of 2, the relative volatility changes only about 5%. For non-ideal systems however pressure may have a more important effect especially when there are azeotropes since the composition of the azeotrope may change with pressure. It may even be possible to eliminate an azeotrope by suitably adjusting the pressure.

A COMMON PROBLEM

It is entirely possible (especially when there is wide variation in the boiling points of the bottom and top product) that the minimum pres-

sure set by the condenser is higher than the maximum pressure set by the reboiler. In this case there are three possible solutions. One is to use refrigeration to condense the top product, but this may be expensive. A second solution is to use a fired reboiler for the bottoms, i.e. send the liquid from the bottom tray to a furnace which may heat to temperatures much higher than condensing steam. The liquid is thus partially vaporized and sent to a flash drum to separate the vapor formed from the remaining liquid. The vapor off this drum is returned to the column below the bottom plate, and the liquid becomes the W product.

A third possible solution to the problem is to accept as a vapor that part of the overhead product which can not be condensed with the cooling medium, i.e. design a partial condenser. The part that is condensed is partly returned as reflux and the rest is liquid D product. The D products thus consist of two streams; one a vapor and one a liquid. This is usually the case for the first crude oil fractionation. The flow sheet is illustrated in Fig. 3.

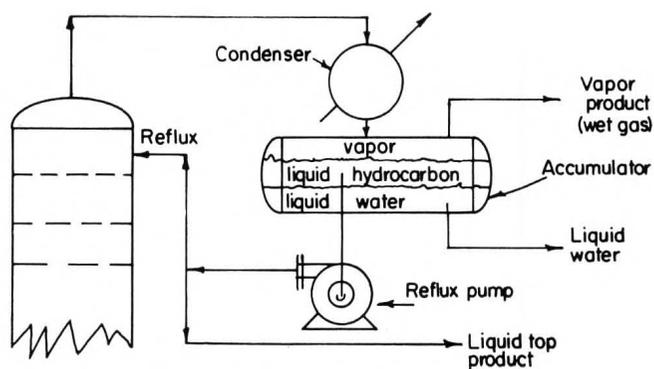


FIGURE 3.

The vapor product contains methane, and ethane which can't be condensed easily. The vapor product is called "wet gas" not because it contains water (which it does), but because it contains some condensible hydrocarbons. It is sent to compressors and thence to an absorption column where the ethane and heavier are removed as ethane and L.P.G. (Liquified Petroleum Gasses) which consist mostly of C_3 's and C_4 's. The methane containing very little ethane and heavier is called dry gas and is about the same as natural gas. The ethane is usually cracked at high temperature to yield ethylene which is the source of many of our petrochemicals.

The liquid water product comes from open steam used to assist in the first crude oil fractionation instead of having a reboiler.

GENERAL FRACTIONATION NOTES

(a) The optimum reflux ratio is said by Treybal to fall in the range of 1.2 to 1.5 times the minimum reflux ratio. This rule was formulated when heat was cheap, say \$0.50 to \$1.00 per million Btu. With currently expensive heat, say \$5.00 to \$8.00 per million Btu the optimum reflux ratio comes much nearer to the minimum and may lie in the range (1.05 to 1.2) (R_{min}).

(b) In desert areas when water is scarce and expensive, air cooling is often used to condense the overhead vapors but in this case the overall heat transfer coefficients are much lower than with water cooling and the optimum approach temperature differences for condensing may be much larger than the 10° to 20°F quoted above. Also the design air inlet temperatures may have to be 90° to 110°F or even 120°F in order to get a design which will work most of the time. □

DESIGN COURSE

Continued from page 29.

projects with gross profit, tax and depreciation schedules are described. Finally, cash flow diagrams are introduced for comparing investments on the basis of simple rate of return, present worth of cash flows, or discounted cash flows.

Given profitability measures, questions of optimality arise. The optimization problem is defined in general terms to begin coverage of this comprehensive subject. The objective is to introduce optimization methods, suggesting the need for further study. Single variable, unconstrained methods known as sequential search methods (e.g., the Golden-Section method) are covered using the excellent descriptions in Chap. 10 of *Digital Computers and Numerical Methods* [2] with two example problems from Chap. 10 of Peters and Timmerhaus (optimal insulation thickness and optimal batch time). Then, multi-variable, unconstrained methods are covered including lattice search, repeated uni-directional search, and optimal steepest descent [2].

Next, the students optimize the design of a distillation tower with a condenser, reboiler, and reflux pump. Throughout the course they have

solved problems involving these components, so for this problem they are given the FORTRAN function DISTIL which computes the rate of return on investment as a function of the product purity, the reflux ratio, and the fractional recovery of the most volatile species in the distillate. The use of DISTIL to (1) carry out material balances, (2) count trays, (3) calculate the tower diameter, heat exchanger areas, and pump horsepower, and (4) calculate costs, cash flows and discounted cash flow rate of return is reviewed. Then, the students write a program to calculate the maximum rate of return on investment. Incidentally, DISTIL was written by Prof. D. Brutvan [1] and has been modified slightly for use in our course. Prof. Brutvan prepared an excellent problem-statement, typical of a large company, with design specifications, sources of physical property data, cost data, and explanations of the algorithm. This has also been modified for use in our course.

After the introduction to process synthesis, the course concentrates on analysis with the configuration of the process flowsheet given. The design variables are adjusted to locate an optimal design for a given configuration. However, in process synthesis, the emphasis is placed upon finding the best configuration. This approach is well-suited to teach methods of increasing the thermodynamic efficiency by heat integration. The monograph, *Availability (Exergy) Analysis* [13] and the paper "Heat Recovery Networks" [11] provide excellent introductions to the analysis of thermodynamic efficiency and the pinch method for minimizing utilities. Synthesis of separation processes is also covered, but briefly in just two hours. The key considerations are introduced, time being unavailable to solve a meaningful problem.

The course concludes with a final exam and the course grade is based upon two mid-semester exams and the homework. Approximately 15 problem sets are assigned, with two problems using FLOWTRAN and one problem in which the rate of return for a distillation tower (using the DISTIL function) is maximized.

SPRING COURSE: PLANT DESIGN PROJECT

Penn's strength in process design can be attributed in part to the large concentration of chemical industry along the Delaware River and to our close interactions with several industrial

colleagues. In this section, organization of the project course to benefit from this interaction is examined, before considering the impact of process simulators.

During the last two weeks of the fall lecture course, the students select design projects suggested by our industrial colleagues and the chemical engineering faculty. The projects must be timely, of practical interest to the CPI, and be workable in 15 weeks. Kinetic and thermophysical property data should be available. Abstracts of possible design projects are prepared and the students select a project or propose one of special interest to themselves. No effort is made to restrict projects to those well-suited for simulation.

In the spring, 1982, we had sixteen projects, one for each group of three students, and in 1983 we had nineteen projects. Each group is advised by one of seven members of our faculty, usually supplemented by a visiting faculty member and a research student in the area of computer-aided design.

During the spring, as the designs proceed, each group meets for one hour weekly (on Tuesday afternoon) with its faculty advisor and one of its four industrial "consultants." For the past three years we have had seven outstanding consultants. Dr. Arnold Kivnick of Pennwalt Corp. has completed his twenty-fifth year as a consultant to our students. Arnold has shared his years of experience in helping our students and young faculty develop their design skills. Other members of our consultant team contribute similarly, making it possible to expose our students to a broad range of design projects.

The course concludes with a one-day technical

FIGURE 5

Abstract of a typical design project

High purity isobutene

(suggested by Len Fabiano, ARCO)

Isobutene will be recovered from a mixed C_4 stream containing n-butane, i-butane, butene-1, butene-2, i-butene, and butadiene. A four-step sequence will be considered: (1) reaction with CH_3OH to MTBE (methyl-tertiary-butyl-ether), (2) recovery of MTBE from the reaction products, (3) cracking of MTBE to methanol, isobutene, and by-products, and (4) recovery of isobutene, by-products and methanol.

This design will concentrate on (3) and (4). Kinetic data in the literature will be supplemented by ARCO.

Fattore, Massi Mauri, Oriani, Paret, "Crack MTBE for Isobutylene," *Hydrocarbon Processing*, 101, Aug., 1981.

TABLE 2
Possible Design Projects (1982-83)

	Suggested by
1. Cyclohexane oxidation to cyclohexanol	W. D. Seider
2. Polymerizer solvent recovery	D. F. Kelley, DuPont
3. High purity isobutene	L. A. Fabiano, ARCO
4. Catalyst recovery plant	L. A. Fabiano, ARCO
5. Triolefin process	L. A. Fabiano, ARCO
6. Ethylene dimerization	L. A. Fabiano, ARCO
7. Ethanol to gasoline	W. B. Retallick, Cons.
8. Methane from coal with K_2CO_3 catalyst	W. D. Seider
9. Liquid CO_2 for extraction of pyrethrin from chrysanthemums	W. D. Seider
10. Syngas to methanol	S. W. Churchill
11. Separation of benzene, toluene, xylene	W. D. Seider
12. Heat pump for ethane-ethylene split	W. D. Seider
13. Optimization of solar heated home	N. Lior
14. Maleic anhydride from butane	W. D. Seider
15. Fluidized-bed, coal combustion, electric power plant	N. Arai
16. Supercritical fluid extraction	A. L. Myers
17. Dimethylamine	P. J. O'Flynn
18. Paramethylstyrene with zeolite catalyst	W. D. Seider
19. Hydrogen production by radiation of CO_2 and water-gas shift	S. W. Churchill

meeting of oral presentations accompanied by written design reports. From the oral and written reports, the faculty selects the outstanding design project for the Melvin C. Molstad Award. Each member of the winning group receives a \$100 prize thanks to the generous endowment of Dr. Ken Chan, Class of 1962. Notably, the last five reports have also won the Zeisberg Award in competition with other schools in our area.

A typical abstract of a design project is shown in Fig. 5 and the titles for 1982-83 are in Table 2. The problems are timely and their diversity shows the broad interests of our faculty and industrial consultants.

IMPACT OF SIMULATORS

Since 1974 we have had access to the FLOW-TRAN program on United Computing Systems (UCS), but its usage has been limited by the high cost of UCS, a commercial computing system. Initially modest funds were budgeted for FLOW-TRAN, but with increasing class sizes and tight budgets it became necessary to charge the

students for use of FLOWTRAN. Consequently, FLOWTRAN was used by just a few groups—as a last resort. The maximum charge per group was approximately \$100.

In 1982, ChemShare Corp. provided DESIGN/2000 as a load module for installation on our UNIVAC/1100 at no cost to the University of Pennsylvania. Subsequently, eight of the sixteen design groups chose to use DESIGN/2000, averaging \$800 of computer charges per group.

DESIGN/2000 has a well-developed thermo-physical property system, CHEMTRAN, with a data bank containing constants for 900 chemicals (as compared with 180 in the student version of FLOWTRAN). Programs are available to calculate constants such as the normal boiling point temperature and critical properties, given the molecular structure (the atom-bond interconnections). For nonideal solutions, programs are available to compute the interaction coefficients for the UNIQUAC equation and, when equilibrium data are unavailable, to estimate activity coefficients using the UNIFAC group interaction coefficients. Furthermore, CHEMTRAN provides the Soave-Redlich-Kwong and Peng-Robinson equations for calculations in the vapor-liquid critical region. In addition to these advantages (compared with FLOWTRAN), alternative programs are provided for short-cut and rigorous analysis of multistaged towers.

Similarly, the PROCESS system of Simulation Sciences, Inc., provides features that are not included in the student version of FLOWTRAN. Some are equivalent to DESIGN/2000, some are not in DESIGN/2000, while some of the DESIGN/2000 features are not included. PROCESS has not yet been installed on our computer, so that we are less familiar with this system.

Several limitations remain and these are gradually being eliminated. However, currently FLOWTRAN, DESIGN/2000 and PROCESS do not model processes with inorganic compounds and ionic species. There are no programs to calculate compositions in phase and chemical equilibrium or to simulate CSTRs, PFTRs, and solids-handling equipment. These features have been included in the ASPEN system, but ASPEN is not yet available for routine student usage. As expected, ChemShare and Simulation Sciences are adding many of the same features.

The bottom line with respect to our design sequence is that industrial process simulators permit more routine analysis of simple processes and

give more accurate analyses for complex processes; for example, extractive distillation towers. These simulators enable more complete parametric analysis and examination of process alternatives. Normally, they are applicable for just parts of the analysis; rarely for analysis of the entire flow-sheet. They provide our students with experience in the use of modern CAD tools.

In our research, the development of new CAD methodologies is emphasized. In the senior design course, some of these methodologies are introduced using well-tested industrial simulators which are gradually upgraded. Emphasis is placed on completing the design. Student time is not wasted working out difficulties with a prototype program.

When possible, process synthesis methodologies are emphasized. As yet, however, few projects have been found which are sufficiently open-ended to permit analysis of many alternate configurations in the fifteen week term. Good suggestions are welcomed. □

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NEW ADSORPTION METHODS

Continued from page 25.

to achieve, but has been extensively studied. Counter-current schemes have included flow in open columns [2, 10, 17]; the hypersorption process where solids flow was controlled by the opening and closing of holes in sieve trays [11], moving belt schemes [12] and the recent magnetically stabilized moving bed system developed by Exxon. The idealized analysis of all these systems will be similar.

A counter-current system is shown in Fig. 6. The solids flow down the column while the fluid flows up. The less strongly adsorbed solute A moves up in zone 1 while strongly adsorbed solute B moves down in this zone. Thus zone 1 purifies solute A. Zone 2 removes solute A from B and thus purifies solute B. In zone 3 solute B is desorbed with desorbent D. Zone 4 serves to remove solute A from the desorbent so that desorbent can be recycled. The desorbent could be water or a solvent.

The solute movement theory can be applied to this system. The solute wave velocities calculated from Eq. (5) or (7) were with respect to a stationary solid. The appropriate fluid velocity is then the interstitial fluid velocity relative to the solid. Thus

$$v = \frac{V_{\text{super}}}{\alpha} + V_{\text{solid}} \quad (18)$$

where V_{super} is the superficial fluid velocity and V_{solid} is the superficial solid velocity. Now u_{solute} calculated from Eq. (5) or (7) is the solute velocity with respect to the solid. The solute

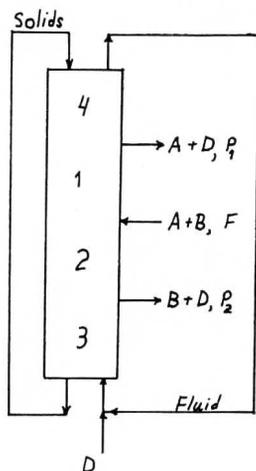


FIGURE 6. Counter-current separator.

velocity which an observer will see is obtained by subtracting the solids velocity

$$u_{\text{solute CC}} = u_{\text{solute}} - V_{\text{solid}} \quad (19)$$

$u_{\text{solute CC}}$ is positive when the solute flow is up the column and negative when it flows down.

In the counter-current column the solids velocity is the same in all zones but the superficial fluid velocity varies from zone to zone since feed is added and products are withdrawn. If we set $V_{\text{super},3}$ as velocity in zone 3, then for relatively dilute systems

$$\begin{aligned} V_{\text{super},2} &= V_{\text{super},3} - P_2/A_C \\ V_{\text{super},1} &= V_{\text{super},2} + F/A_C \\ V_{\text{super},4} &= V_{\text{super},1} - P_1/A_C \end{aligned} \quad (20)$$

Since V_{super} changes, $u_{\text{solute CC}}$ will change from zone to zone. In addition, if the desorbent affects the adsorption of solute then the equilibrium

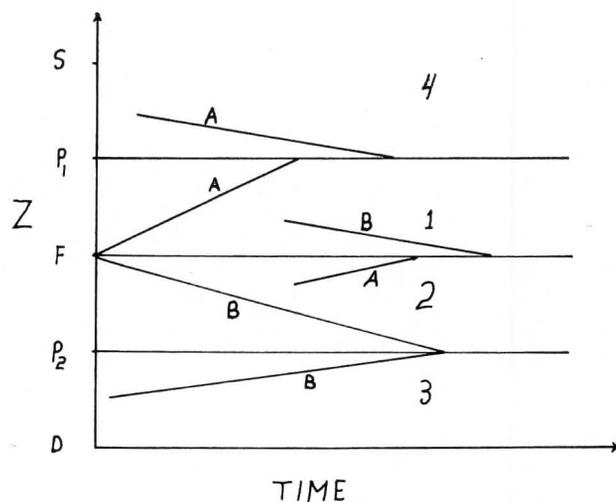


FIGURE 7. Solute movement in continuous counter-current column.

constant $A(T)$ will vary from zone to zone and $u_{\text{solute CC}}$ will change. This latter effect is not necessary to make the counter-current column work.

To achieve the separation indicated in Fig. 6 we want solute A to move upward in zones 1 and 2 and downward in zone 4. Thus

$$u_{A \text{ CC},1} > u_{A \text{ CC},2} > 0 > u_{A \text{ CC},4} \quad (21)$$

Solute B should move downwards in zones 1 and 2 and upwards in zone 3. Thus

$$u_{B \text{ CC},3} > 0 > u_{B \text{ CC},1} > u_{B \text{ CC},2} \quad (22)$$

An alternative to continuously moving solid down the column is to move solid and entrained fluid down in pulses. This is commonly used in continuous ion exchange systems such as variants of the Higgins system and the Graver Water Treatment System. This system could also be applied to the binary separator.

Eqs. (21) and (22) are an important result since they control the operation of the continuous counter-current column. There is a range of values for P_1 , P_2 and D for a given feed flow rate which will satisfy inequalities (21) and (22). In actual practice it is desirable to choose the flow rates so that all the inequalities are as large as possible.

The appropriate solute waves are shown in Fig. 7. In the ideal case at steady state there will be no solute A in zones 4, 2 or 3 and no solute B in zones 1, 3 and 4. Because of dispersion and finite mass transfer rates solute A will appear in zones 4 and 2, and B will be in zones 1 and 3. The size of the zones required depends on these dispersion and mass transfer rate effects. In addition, any axial solid or fluid mixing caused by non-perfect flow will require a larger column. Extreme mixing or channeling can destroy the desired separation.

COUNTER-CURRENT OPERATION II. Pulsed Flow

An alternative to continuously moving solid down the column is to move solid and entrained fluid down in pulses. This is commonly used in continuous ion exchange systems such as variants of the Higgins system [10, 18, 20] and the Graver Water Treatment System [14]. This system could also be applied to the binary separator shown in Fig. 6.

In the pulsed system the solid is stationary except for short periods when it moves down. Thus u_{solute} is given directly by Eq. (5) or (7) with the superficial fluid velocities given by Eq. (20). When the solid and fluid are pulsed downward, the solute waves are also shifted down. The solute wave theory for the pulsed flow system is shown in Fig. 8. The net movement of solute A is upward in zones 1 and 2 and downward in zone 4. The net movement of solute B is downward in zones 1 and 2 and up in zone 3. Fig. 8 is drawn for a plug flow movement of solids and fluids during the downward pulse. Feed would be introduced continuously and withdrawn continuously. Only one feed period was shown to keep the figure simple. If mixing occurs during the pulse less separation will be obtained. This is a practical limit to sharp

fractionation of two solutes in a pulsed flow counter-current system.

$$V_{\text{solids,avg}} = l_p/t_p \quad (23)$$

where l_p is the length of a pulse movement in meters and t_p is the time between pulses in minutes. The average solute velocity over many pulses is given by Eq. (19). The desired separation will be achieved when inequalities (21) and (22) are satisfied.

SIMULATED COUNTER-CURRENT SYSTEMS

An alternative to moving bed systems is to simulate counter-current movement. This is done with a series of packed bed sections by switching the location of all feed and product withdrawal ports. An observer located at a product withdrawal port sees the solids move downwards everytime

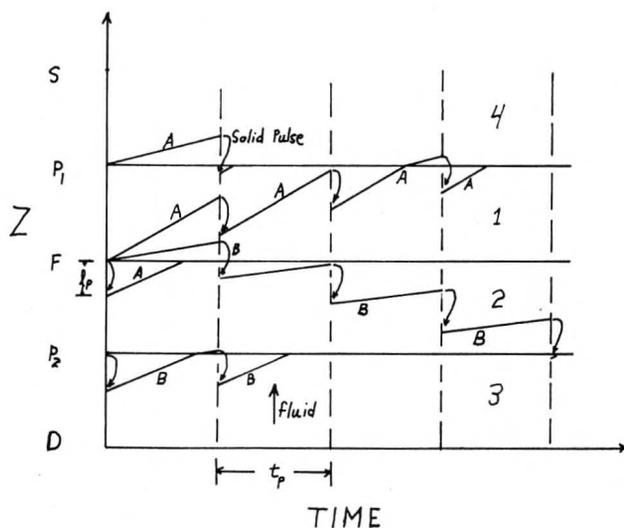


FIGURE 8. Solute movement in pulsed counter-current system.

the port location is shifted upwards. Thus the observer sees a process very similar to the pulsed counter-current system analyzed in Fig. 8.

The first simulated counter-current system was the Shanks system which has been applied to leaching, adsorption and ion exchange [13, 21]. The Shanks system uses a series of columns with plumbing arranged so that feed can be input and

t_{port} is the time between switches of ports. The conditions to achieve separation are then

$$u_{A,1} > u_{A,2} > u_{port,avg} > u_{A,4} \quad (25)$$

$$u_{B,3} > u_{port,avg} > u_{B,1} > u_{B,2}$$

These conditions follow the same order as Eqs. (21) and (22).

How close is a simulated counter-current system to a truly counter-current separator? Although the answer to this depends on the chemical system and the column length, Liapis and Rippin [15] found that the simulated system had an adsorbent utilization from 79% to 98% that of the truly counter-current system. With a single zone system they found that from two to four sections were sufficient and that two to four column switches were required to reach a periodic concentration profile.

Comparison of simulated counter-current and truly counter-current systems is of considerable interest. Both systems at steady state can at best do a complete binary separation. Partial separation of additional components can be obtained with side withdrawals. The simulated counter-current system could also be extended to more complex cycles where part of the bed is temporarily operated as a batch chromatograph. The simulated moving bed system is actually a fixed bed system. Thus flooding (unintentional upwards entrainment of solid) will not be a problem, but excessive pressure drop may result for small particles or viscous solutions. The fixed bed will have a lower α and hence a higher capacity than truly counter-current systems, but this will be offset by the distribution zones between sections. The actual movement of solids requires means for keeping the bed stable, may result in excessive attrition, but allows for easy solids replacement or external reactivation. Both systems have mechanical difficulties to overcome. In the simulated moving bed these difficulties are the valving and timing while in an actual moving bed they involve moving the solids without mixing. Currently, the simulated counter-current systems have been the preferred choice for large-scale adsorption installations. □

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NOMENCLATURE

A (T)	—Equilibrium parameter, Eq. (6)
A_c	—Cross sectional area of column
c	—Solute concentration in fluid, kg/L
C_f	—Heat capacity of fluid
C_s	—Heat capacity of solid
C_w	—Heat capacity of wall
F	—Feed rate, L/min
k	—Exponent in Freundlich isotherm, Eq. (14)
K_d	—Fraction of interparticle volume species can penetrate, Eq. (1)
l_p, l_{port}	—Length of travel of pulse, or packing height between ports, m
L	—Column length, m
P_1, P_2	—Product flow rates, L/min
q	—Amount of solute adsorbed, kg/kg adsorbent
t	—Time, min
t_p	—Time between switching port locations, min
T	—Temperature, °C
T_f, T_s, T_w, T_{ref}	—Temperature of fluid, solid, wall and reference
T_C, T_H	—Cold and hot temperatures
u_A, u_B, u_{solute}	—Solute wave velocity, m/min, Eq. (5) or (7)
u_{shock}	—Shock wave velocity, m/min, Eq. (17)
$u_{thermal}$	—Thermal wave velocity m/min, Eq. (9)
v	—Interstitial fluid velocity, m/min
V_e	—Elution volume of non-adsorbed species, L
V_i	—Internal void volume, L
V_o	—External void volume, L
V_{solid}	—Solid velocity, m/min
V_{super}	—Superficial fluid velocity, m/min
W	—Weight of column wall per length, kg/m
z	—Axial distance in column, m
α	—Interparticle void fraction
ϵ	—Intraparticle void fraction
Δ	—Difference calculation
ρ_s	—Solid density, kg/L

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BOOK REVIEW: Carnegie-Mellon

Continued from page 37.

Obviously the book is not intended for use in the usual academic sense and its particular audience is the many people . . . faculty, staff and students . . . who have contributed to chemical engineering at Carnegie over the years. It can also serve as a guide to those considering similar undertakings at their own institution in pointing out the monumental effort involved. Admittedly, this reviewer is not wholly unbiased in consideration of this volume inasmuch as he has spent almost half of his academic career at Carnegie, but he can attest to a considerable portion of the accuracy of Professor Rothfus' many details. Its delightful reading!! □

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