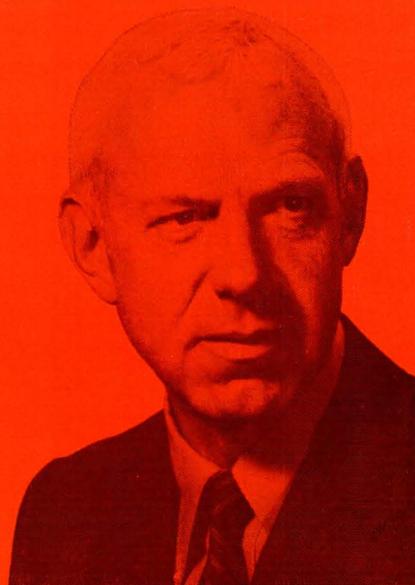


WEST VIRGINIA'S PRIDE PROGRAM

BOB REID
of
M. I. T.



SPECIAL KINETICS AND THERMO ISSUE

LEVENSPIEL—Cold Lips, Warm Heart & Thermo

FAN AND LIN—Transients in Plug Flow Systems

HUDGINS—Catalytic Reactor Stability

GATES AND SHERMAN—Heterogeneous Catalysis

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FEATURES

- 115** Self Instruction in Thermodynamics
Frank Tiller
- 118** Carberry's Ultimate Paper
Aris Rutherford
- 128** Pollution of the Environment—
Causes and Cures
M. Hawley, M. Chetrick and E. Shaheen

DEPARTMENTS

- 106** The Educator
Bob Reid of M.I.T.
- 110** Departments of Chemical Engineering
West Virginia University
- 102** Views and Opinions
Hot Lips, A Cold Heart and
Thermometry
O. Levenspiel

Classroom

- 120** Transients in Plug Flow Systems
L. Fan and S. Lin
- 133** Use of a Continuous System Simulation
Language in Chemical Reaction Engineering,
R. Williams and D. Wolf

Laboratory

- 124** Experiments in Heterogeneous Catalysis
B. Gates and J. Sherman
- 138** Demonstrating Catalytic Reactor
Stability, *R. Hudgins*

Curriculum

- 144** Georgia Tech's Pulp and Paper Program
G. Lightsey

139, 143 Book Reviews

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HOT LIPS, A COLD HEART AND THERMOMOMETRY

OCTAVE LEVENSPIEL

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Corvallis, Oregon 97331*

THE ORIGIN OF THE THERMOMETER, a device with some sort of scale for measuring the hotness or coldness of objects, is obscure. However, the climate in Europe in the beginning 1600's was hot for it, it had to be invented at that time, and so it was . . . but by whom? In Italy Galileo had his champions, and so had Santorio, Professor of Medicine at Padua. Then there was the Welsh doctor and religious nut Fludd; also the gadgeteer, inventor, and perpetual-motion-machine-maker, Drebbel of Holland. But who was first? Since people in those days didn't much care about getting into the Guinness Book of Records we probably will never satisfactorily resolve this question. It seems that this sort of immortality was not the passion then that it is today.

In any case, by the middle of the 1600's the thermometer was widely known in Europe, each maker having his own scale of measurement. A popular design started with "1" in the middle of the device to represent everyday comfort. It then indicated 8 degrees of coldness and 8 degrees of hotness, each degree in turn divided into as many as 60 minutes. Other makers were more descriptive, viz

Extream Hott
Very Hott
Sultry
Hott
Warm
Temperate
Cold
Frost
Hard Frost
Great Frost
Extream Frost

Even as late as the middle 1800's one could buy a thermometer having 18 different marked scales.

The development of a standardized temperature scale was a long and bumbling process. About 100 years after the invention of the thermometer enter Daniel Gabriel Fahrenheit, Danzig born, Dutch

adopted, master instrument maker, and traveller. While in Copenhagen in 1704 or 5 (or maybe 6) he visited Ole Rømer, Danish astronomer, where he observed him busily calibrating thermometers. Struck by the elegant simplicity of Rømer's choice of calibration points . . . $7\frac{1}{2}^{\circ}$ for the ice-water and $22\frac{1}{2}^{\circ}$ for body temperature, Gabe immediately adopted these for his own. But since fractions always bothered him he eventually multiplied everything by 4 to get rid of the two halves, fudged upward a bit, and ended up with 32° and 96° for these calibration points. On this scale a mixture of sea salt and ice melted at about 0° and

The temperature measures the "quantity of heat" in a body, or in today's language, "thermal energy." So "why not measure temperature directly." Georgian, an American engineer, strongly urges we adopt such a scale choosing the ideal gas as measuring instrument.

water boiled somewhere between 200° and 240° (say 212° as a good average). Because humans are somewhat unreliable, some hot blooded, others questionable, before long the freezing point (32°) and the boiling point of water (212°) became the accepted calibration points. Since Fahrenheit's thermometers sold well this scale soon became widely adopted.

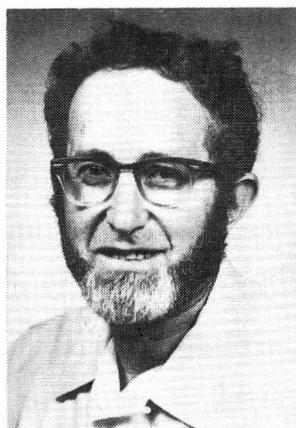
PARTY PLEASER

IT WAS QUITE A MARVEL in those days to put ice and a liberal helping of salt in a pan, insert a thermometer and see it zonk down to 0°F and stubbornly refuse to budge . . . even with the pan on a hot stove! But in our age of TV marvels we may have to dress up this experiment to catch anyone's attention. Here is one way, best done at a large party or gathering. Bet a particularly obnoxious fellow \$10 that he cannot keep his foot in a pan of salt and ice for 10 minutes.

Sit him down and while his foot is freezing solid get hold of a hammer. After 10 minutes his pain is gone and you are ready for the finale to this demonstration. Remove his foot from the pan and strike his big toe firmly with the hammer. The brittle toe will snap off and fly across the room. Accompanied by "ooohs" and "aaahs" retrieve this toe and in a matter-of-fact way return it with \$10 to the surprised owner. This spectacular ending will guarantee that you and thermometers will be the talk of the town for a long time to come.

To return to the thermometer, while Gabe's came into wide use in England and Holland, the French completely ignored this Northern development. Their man was Réaumur who after 1731 vigorously championed a spirits of wine thermometer . . . French wine, of course, and red for easy reading. His scale went from 0° for ice water to 80° for boiling water. Unfortunately, however, among other things Réaumur's insistence on a one-point calibration and the fact that the quality of French wine varied from year to year, led to all sorts of complications. So although the French gave this thermometer a good try for over a century, they eventually gave it up; and drank their wine instead.

While these developments were taking place in warmer climes Swedish astronomer Anders Celsius tramped his snowy land with 10 cold fingers and 10 cold toes advocating a 100 division scale (centigrade) by continually proclaiming "water boils at 0°, water freezes at 100°, boils at 0°,"



Octave Levenspiel, professor at OSU, is primarily interested in problems of chemical reactors. He has written a text on this subject, and has won the ASEE Lectureship Award for his early visions in this field.

His weakness for scientific curiosities has led to flirtations with 4-colorologers, 2nd law repealers, Fibonacciics, boomerologists, topographers, and other such. He is also 1975 president of the Northwest Neothermo Society.

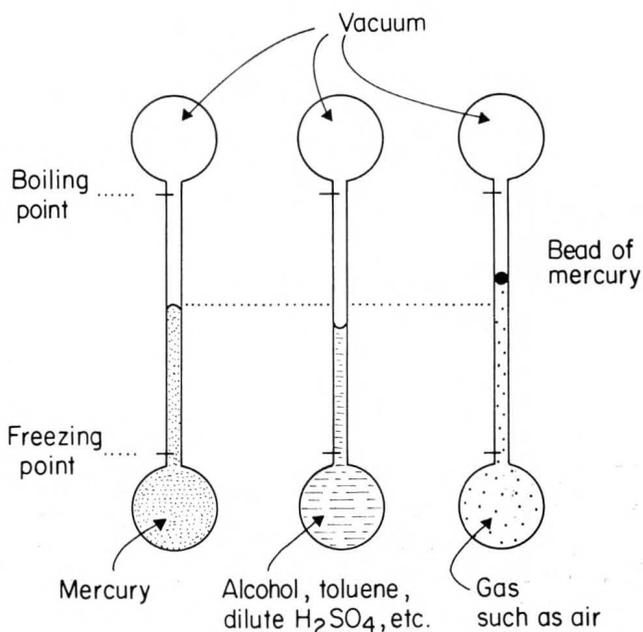


FIGURE 1.

freezes at 100." By happenstance however, Anders' intimate friend, Linnaeus, the great botanist, was left-handed. Because of this he kept snatching the wrong end of the instrument and using it upside down, and kept reading 0° for the freezing point and 100 for the boiling point, and thus recommended this scale.

To confuse the issue further there were other strong claimants for the honor of inventing this scale; nevertheless, in 1948 the 9th General Conference of Weights and Measures decided that it knew enough, it dismissed all the others, and ruled that what had been known as °Centigrade should henceforth and forever more be known as °Celsius. And so Celsius' name will be with us forever, and all because he chose his parents wisely. Had Linnaeus' name been Clinnaeus we might today be talking of °Clinnaeus instead of degrees Celsius.

CALIBRATION CONFUSION

THERMOMETERS EVOLVED into three broad types, as shown in Fig. 1, and as users became fussier and demanded more precision all sorts of problems cropped up. For example, should melting ice or freezing water be one of the calibration points? In practice they differ! Should boiling water or condensing steam be the other? The zero point also slowly and continually changed with time. In mercury thermometers it crept upward, in alcohol thermometers it slid downward.

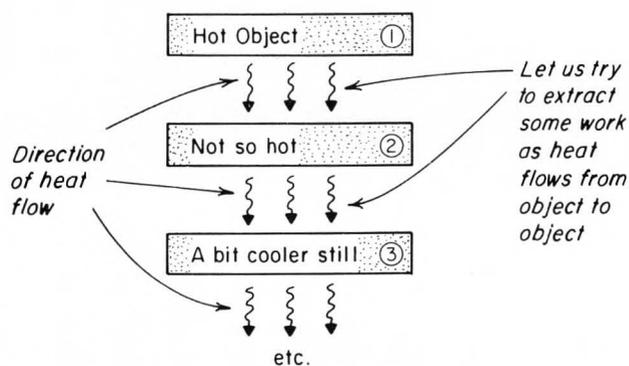


FIGURE 2.

Was this due to the aging of glass, the slow decomposition of the fluids, or what? And these changes continued for 10, 20, 30 years!! Also, how did these scientists explain the small periodic variations according to season!!?

Probably the most serious problem was that when one type of thermometer read a temperature halfway between calibration points the others did not because of changing coefficients of expansion of fluids. This is illustrated in Figure 1. In this case which thermometer read the true midpoint temperature—which to trust? Was the selection of equal intervals of temperature an arbitrary matter, or was there a rational way for doing this? These difficulties kept scientists out of mischief for quite a while.

In the 1800's there was much concern about developing a rational temperature scale. In 1847 Regnault pinpointed the problem by stating:

“We give the name *thermometer* to instruments intended to measure the variation of the quantity of heat in a body . . . A perfect thermometer would be one whose indications are always proportional to the quantity of heat absorbed, or, in other words, one in which the addition of equal quantities of heat always produces equal expansions . . . Unfortunately this is not so for real substances.”

Just a year later William Thomson, later Lord Kelvin, magically devised just such a temperature scale based upon the concept of the ideal reversible heat engine of Sadi Carnot. To illustrate its basis, imagine a number of objects or heat reservoirs arranged from hot to cold as shown in Fig. 2, and let heat flow from one to the other while doing as much work as possible.

Suppose that 100 units of heat leave reservoir 1 for reservoir 2, and in the process are able to do 10 units of work in the most efficient engine conceivable. Then 90 units of heat reach reservoir 2. Suppose these 90 flow on, doing 10 more units of

work before reaching the next reservoir, and so on.

Kelvin argued that we should choose a temperature scale which is proportional to this heat flow. Any proportionality would do, thus 100, 90, 80°, etc. or 250, 225, 200°, etc., for the sketch shown in Fig. 3. Scales such as these are now called Absolute temperature scales.

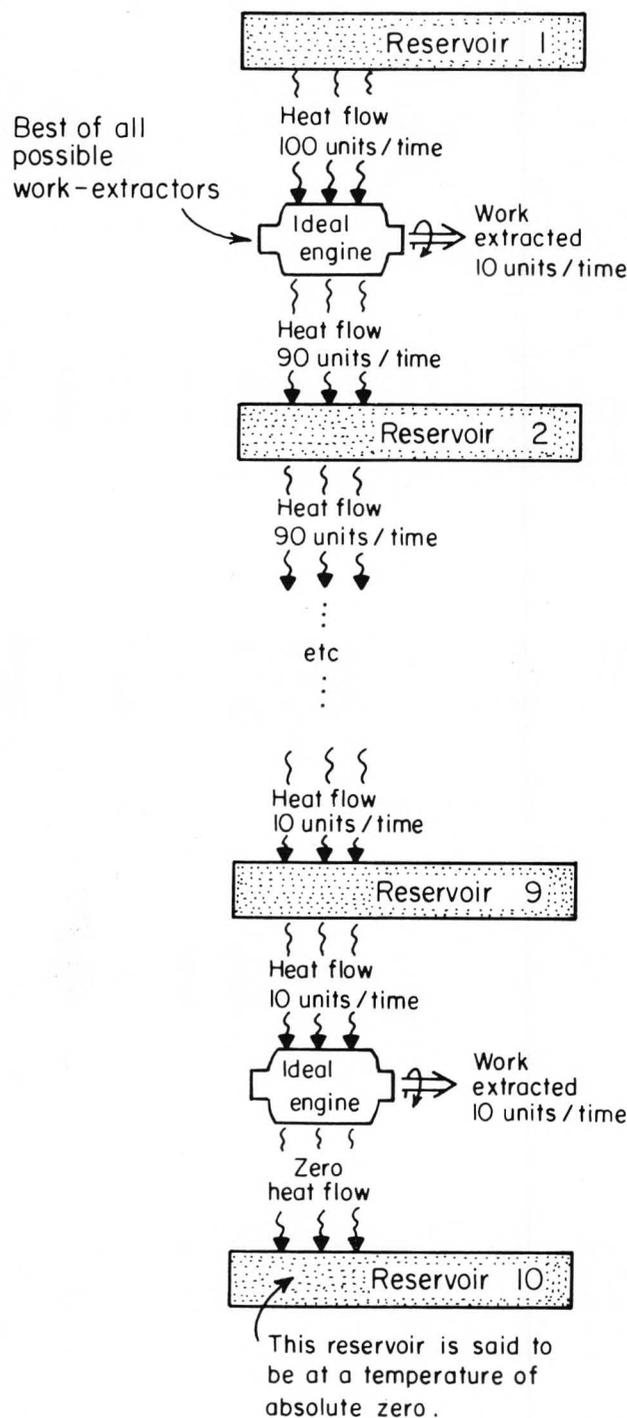


FIGURE 3.

An interesting bonus to this argument of Kelvin's is that since no heat enters the lowest reservoir of Fig. 3 none can leave it to flow to an even colder one. Thus this bottom reservoir in the sketch must be the lowest imaginable of temperatures, the ABSOLUTE ZERO of temperature. What a jewel of an idea this turned out to be.

On this basis we now commonly use two scales; the Kelvin scale corresponding to degrees Celcius and the Rankine scale corresponding to degrees Fahrenheit. These are sketched in Fig. 4.

Today, more than 100 years later, how pure do we find his conclusions? Giant refrigeration machines fueled by Nobel prizes help us freeze our way even closer to this "THOU SHALT NOT TRESPASS" limit, yea, within a thousandth of a degree, but Kelvin's limit still stands unshaken and confident.

Finally Kelvin found that simple gases at very low and constant pressures occupied volumes proportional to their absolute temperature, and therefore provided a practical way for accurately calibrating thermometers.

TEMPERATURE TODAY

SO HERE IS HOW THINGS stand today. First of all the lowest possible temperature imaginable, the absolute zero, has been invented. This is where our temperature scales should start from, and this is where our absolute scales ($^{\circ}$ Kelvin and $^{\circ}$ Rankine) in fact do. Secondly, we have a rational way for choosing equal intervals of temperature.

We just have one question left. Starting from this cold cold zero point, why pick our unit of temperature the way we do? Why base it on 100 intervals or 180 intervals between the freezing and boiling point of water? Why pick water, why not googliox? Isn't there a more reasonable way of selecting our unit of temperature?

As Regnault long ago pointed out, the temperature measures the "quantity of heat" in a body, or in today's language, its "thermal energy". So why not measure temperature directly as energy per unit quantity of material. Georgian, an American engineer, strongly urges that we adopt such a scale choosing the ideal gas as measuring instrument. The reason for this is that the energy of any ideal gas is proportional to its absolute temperature. So measure its energy and you've got its temperature.

The sketches in Fig. 5 compare various possible absolute temperature scales following this

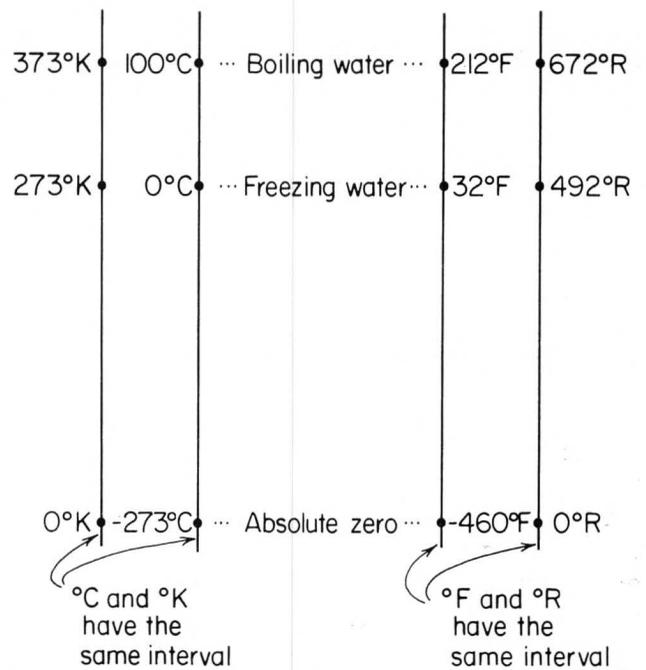


FIGURE 4.

proposal. Because of its compatibility with the SI units Georgian particularly favors the last of these scales, or joules/kmol.

It may seem awkward and foreign to talk of water freezing at 2270°X , boiling at 3100°X , and of having a mild fever of 2600°X (where X would then honor some famous scientist whose name does not start with the letters C, F, K or R). However, you must admit that it would be a smashing bit of one-upmanship to sprinkle one's talk this way. But more seriously, with such a scale a number of simplifications occur naturally. In particular it would forever banish one conversion (Continued on page 137.)

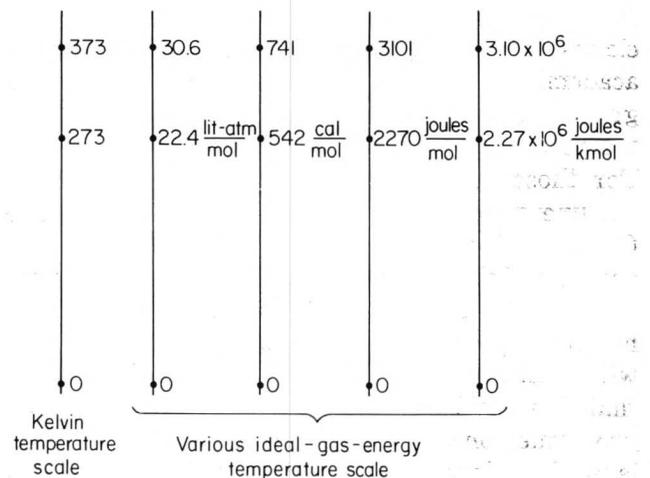


FIGURE 5.

Bob Reid of M. I. T.

MICHAEL MODELL

*Massachusetts Institute of Technology
Cambridge, Massachusetts 02139*

USUALLY, BOB REID IS IN class five minutes before the hour to greet and chat with early arrivals to his 9 a.m. graduate thermodynamics course. This day, the students find instead, coffee and doughnuts set up in the back of the room. At the bell, Maria (Bob's secretary) announces: "Unfortunately, Professor Reid

In spite of the fact that the graduate thermo course is known to be the toughest, most demanding course in the program, Bob was chosen by the students as the Outstanding Teacher in the Department in 1973 and again in 1975.

couldn't make it today, but he has sent a guest lecturer, J. Willard Gibbs." She proceeds to lead in a decrepit old man, dressed in an academic gown and made up in a wig, false nose and glasses. Leaning heavily on a cane, he presents a fascinating, but incoherent lecture on the criteria of equilibrium and stability. The contrast with one of Bob's lectures, which are usually marked by clarity and simplicity without any trace of academic arrogance or pretension, couldn't be greater. But it's all in fun, because the man in the gown is Bob himself. Unexpected? Not really. For those fortunate enough to know Bob Reid, the unexpected often becomes the expected. The Gibbs routine is pure RCR. It's just one of many gestures Bob makes to develop a close rapport with the students. Early in the term, for example, he invites every entering graduate student to chat with him for a half hour. "I try to show them that the inside of my office is really not very grotesque; once they've been in, the second time is much easier." And they do come back, time and again, to discuss their interests and problems,

and to seek his counsel. In spite of the fact that the graduate thermo course is known to be the toughest, most demanding course in the program, Bob was chosen by the students as the Outstanding Teacher in the department in 1973 (the second year the award was given) and again in 1975.

Bob's interest in chemistry, as well as his classroom sense of humor, date back to his high school days in Denver. He recalls his chemistry teacher, who conducted a qualitative analysis lab. "He used to give us all sorts of fascinating samples. He was quite a joker. He'd give you powdered concrete as an unknown. Your first reaction was to see if it dissolved in water. It would set up like a rock overnight; then he'd get the biggest kick out of seeing your reaction the next day. He was the kind of teacher a student could relate to. He'd have a standing challenge that any student who could beat him in shooting baskets would automatically get an A, regardless of how little chemistry the student knew."

QUESTIONABLE BACKGROUND

BOB'S COLLEGE EDUCATION could best be described as sporadic. He entered Colorado School of Mines in 1942, majoring in petroleum refining because "I was offered a scholarship and petroleum refining was the closest offering to chemistry." But he didn't stay long: "In my freshman year, I turned eighteen, quit school, and joined the Army Air Corp as a cadet. After eight months, I contracted rheumatic fever and was given a medical discharge. I drove a truck, worked in a steel mill, went back to school, and then joined the Navy in 1943. The computers weren't very good in those days; before I was discharged in 1946, I think I was the only one in the country with an active commission in the US Navy and a medical discharge from the Army."

After the war, Bob returned to Colorado School of Mines, where his candor and curiosity almost led to several suspensions. "I used to argue in class and most professors didn't like a



Unfortunately Prof. Reid couldn't make it today, but he has sent a guest lecturer, J. Willard Gibbs.

student questioning their presentation. This is why, even now, I feel very strongly that a student should raise questions—on everything I say, on everything I do.”

After his junior year, he transferred to Purdue, where he obtained B.S. and M.S. degrees in chemical engineering, and where he met Joe M. Smith. “Joe really turned me on; he was the first teacher who gave me problems I couldn't solve. As a matter of fact, I'm still using some of them. I had never met a professor who wanted to know you as an individual. If I were working in the lab late at night, he'd stop in, put his feet up on the desk, and talk with me, not necessarily about my thesis, but about almost anything.”

“Warren K. Lewis was another teacher who had a great impact on me. I'll never forget one of my first classes with Doc after I entered M.I.T. in 1951. He gave us a homework assignment and I put in a lot of time on it; I thought I had it cold. When he called on me to do the problem, I breezed through my solution and knowledgeably commented on it. Well, he stood there and looked at me, horrified. Then he marched down the aisle, poked that finger of his in the middle of my face, and said in his inimitable fashion, ‘Go-o-o-d da-m-m-it, Reid, you don't re-a-a-ally believe that!’ Everybody in the class was staring at this little character, scrunched up in his seat and wondering what he'd say. You see, either you were firmly convinced that you were right and were willing to argue with him, or you had to

think of another answer awfully fast. I had the right solution, and he knew it, but he forced his students to develop confidence in their own convictions and to learn how to defend their positions. That was an experience I'll never forget, and one I've tried to emulate.”

FIRST OF MANY CHAPTERS

BOB BEGAN HIS TEACHING career as an Instructor while finishing his Ph.D. dissertation in 1954. He was teaching an undergraduate thermo course with Tom Sherwood. At one point, the two of them were trying to make out a refrigeration problem, involving a mixture of refrigerants. Bob recalls, “We couldn't find some boiling points or critical pressures, and so Tom turned to me in disgust and said, ‘Reid, somebody ought to write a book that tells you how to estimate these things if they're not in the literature.’ About a month later, Bob dropped a chapter and an outline for a book on Tom's desk. Tom was so shocked that he agreed to co-author the book. Bob finished the manuscript while he was Director of the School of Chemical Engineering Practice at Oak Ridge. The rest is well-known history. The first edition of *Properties of Gases and Liquids* was printed in 1958, received rave reviews, and has been an essential part of every chemical engineer's library ever since. The second edition was printed in 1966 and has since been translated into Russian and Spanish. Bob is currently working on the third edition.

**The first edition of
Properties of Gases and Liquids
was printed in 1958, received rave reviews,
and has been an essential part of every
chemical engineer's library ever since.**

Bob has also co-authored two other books: *Modelling Crystal Growth Rates from Solution* (with M. Ohara, 1974) and *Thermodynamics and its Applications* (with M. Modell, 1974).

Bob joined the faculty at M.I.T. ostensibly to finish *Properties of Gases and Liquids*. One thing led to another, and Bob has been at the Institute ever since. Although Bob considers himself to be inbred, he has consistently been at the forefront of movements for change and improvement: in curricula, in graduate school policy, and in faculty

Joe Smith really turned me on; he was the first teacher who gave me problems I couldn't solve. As a matter of fact, I'm still using some of them . . . I had never met a professor who wanted to know you as an individual. Warren K. Lewis was another teacher who had great impact on me . . . he forced his students to develop confidence in their own convictions and to learn how to defend their positions.

hiring policy. He has been opposed to M.I.T.'s long-standing policy of hiring its own Ph.D.'s as assistant professors. "For many years, inbreeding worked in M.I.T.'s favor, but today there are numerous first-rate chemical engineering departments around the country, each with its own style and qualities, and it's high-time we cross-fertilized students and faculty with other schools. I am pleased to see that we're making concrete progress in that area."

In his most recent crusade, Bob assumed the editorship of the ailing AICHE Journal in 1970. In a short time, he introduced much needed reform and pioneered innovations in ways of disseminating technical knowledge. To be a journal editor, one must have patience and tact in dealing

with authors, many of whom have strong convictions, and some of whom regard their manuscripts as sacred prose. The fact that he remains on good terms with them, and is highly admired by many of them, is a tribute to his skill and finesse. He has managed to inspire confidence once again in potential contributors, mostly by reducing hold-up time for manuscripts, but also by careful and fair attention to reviewer's comments as well as the author's special wishes and needs. His performance has earned him deep respect from a large and increasing following. In this capacity alone, he has probably contributed more to our profession in just a few years than many of us will be able to accomplish in a lifetime. □

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WEST VIRGINIA

... and its
**"Pride
 Program"**



ChE DEPARTMENT FACULTY
West Virginia University
Morgantown, West Virginia 26506

IN THE COAL-RICH mountains of West Virginia, the '70's will undoubtedly be remembered as the decade of the energy crisis. The state's abundant supply of coal brought it new prominence as an energy supplier; but with that prominence came questions. How could the coal be mined cheaply without destroying the rugged beauty of the state? How could its high sulfur content be treated so that it could be burned without polluting the air?

The young men and women who are today's chemical engineering students are eager to take a hand in answering these and other questions; yet when the time comes, that step out of the classroom into a job is a big one. Recognizing the uncertainty students are likely to experience making that transition, West Virginia University's Department of Chemical Engineering has developed a program aimed at enabling students to apply ChE concepts to complex real world problems.

Called PRIDE, the program combines individualized instruction, increased emphasis on design courses, and programmed instruction to provide **Professional Reasoning Integrated with Design Experience**.

The PRIDE concept was developed at WVU over a number of years. Dr. H. P. Simons, former department chairman, took the first step in the early '60's when he introduced the Senior Block, a 10 credit course taken both semesters of the senior year. The content of traditional fourth year studies were incorporated into the block's year-long comprehensive design project.

Later, a unique course called "Guided Design" was introduced for all freshmen engineering students. Planned, controlled projects are emphasized in this course aimed at developing the student's ability in analysis, synthesis and evaluation.

The PRIDE program has four basic objectives:

- To present a coordinated, professional ChE curriculum oriented more toward the education of practicing engineers than research engineers.
- To involve the student in the team-effort approach to solving engineering problems.
- To take advantage of faculty specialties in each area by the use of team-teaching.
- To utilize programmed instruction and other innovative educational techniques to achieve maximum efficiency in the teaching of content subject matter.

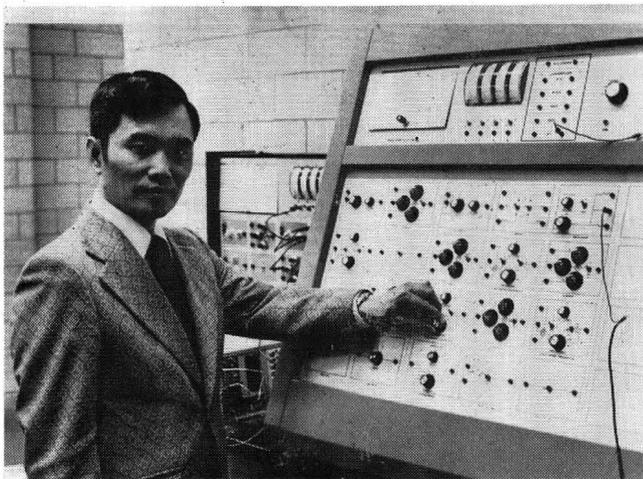
Recognizing the importance of design proficiency for the professional engineer, WVU's ChE faculty resolved to introduce this complex activity early and to give students frequent opportunity to practice it.

In 1972 a grant was awarded by the Exxon Education Foundation to fund the development of this program in the sophomore and junior years. Now, over three years later, most of the "bugs" seem to have been worked out and the program is operating smoothly.

Al Pappano directs the sophomore segment of PRIDE, a two semester (two/credit/semester) course. The Junior Block, supervised by Duane Nichols and Dick Bailie, consists of two three-credit courses taught back-to-back each semester, allowing several uninterrupted hours of class time.

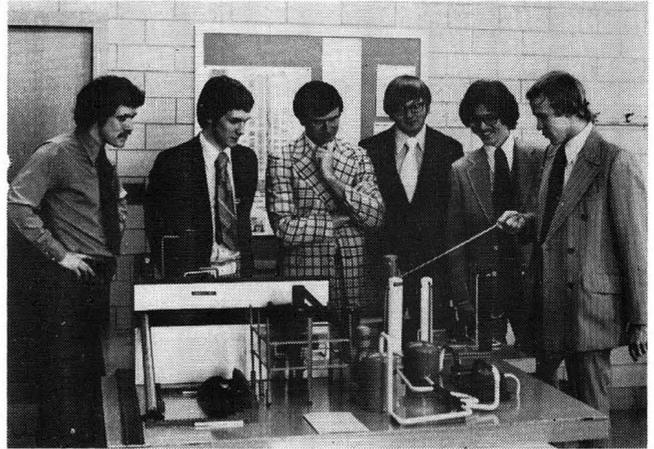
Faculty members guide the students to complete the projects themselves. In these classes, the student plays the role of a professional engineer on a four-man team trying to solve a design project problem.

Each design problem presented is carefully chosen to require knowledge of the concepts which make up the course content. Students learn subject material based on a "need to know" in order to complete the design project.



Dr. C. Y. Wen, Department Chairman, heads research activities in coal/energy research.

The role of the instructor changes as the students progress through the program. Moving away from the traditional role of transmitter of knowledge, the instructor becomes a consultant who guides the student's decision-making activities.



Senior Block group leaders look over plant model.

SENIOR DESIGN PROJECT

THE SENIOR BLOCK, DIRECTED by Fred Galli and John Sears, is the culmination of this practice in decision-making and design work. Planned to simulate as nearly as possible the working environment of the practicing engineer, the focus of the senior curriculum is a comprehensive design project. Students meet every week in uninterrupted class periods to work on this project.

Each fall the student chief engineer, who is recommended for the job by the previous year's graduating class, receives from the faculty a brief description of the project to be undertaken. For example, the recently graduated chief engineer, David Daugherty, guided his class in an exploration of the use of alcohol as a gasoline extender, a topic particularly relevant in these days of high fuel prices.

The project description specified the volume of alcohol to be produced each day and identified the particular processes to be used to produce ethanol or methanol from wood or coal. The class divided into five groups to investigate these processes and to study the economics of each one. As their planning became more exact, the group considered environmental and safety concerns. They found that some processes presented special problems. For instance, all of the wood in Pennsylvania was needed as a raw material for one of the processes.

When the class reached agreement on the most feasible process, a detailed design and economic analysis was conducted to determine what effects factors such as fluctuation in material costs or changes in the nation's financial outlook would have on the cost of production. Construction of a plant model was the last step in completing the project.

WVU ChE department is perhaps the only place on campus where students are enthusiastic about examinations, recognizing the learning opportunity they present.

At the final presentation, each group leader summarized the group's contribution to the project and answered questions posed by faculty and students. This occasion gives students a chance to demonstrate their creativity and it becomes apparent that the program isn't called PRIDE by accident.

Students also have a chance to display their expertise during another feature of the Senior Block, the major examination. When a "major" is scheduled, all senior ChE classes are cancelled and students work individually for one or two weeks on a process analysis project proposed by the faculty. The project is designed to develop student maturity—and judgment counts as heavily as the student's performance on the "major." Creativity and judgment count as heavily as design proficiency. Students present a written report of their work and defend it orally before a faculty panel. The oral presentation is particularly valuable because students get experience in presenting and defending their ideas before a technically trained group. The WVU ChE department is perhaps the only place on campus where students are enthusiastic about examinations, recognizing the learning opportunity they present.

COMMUNICATIONS SKILLS

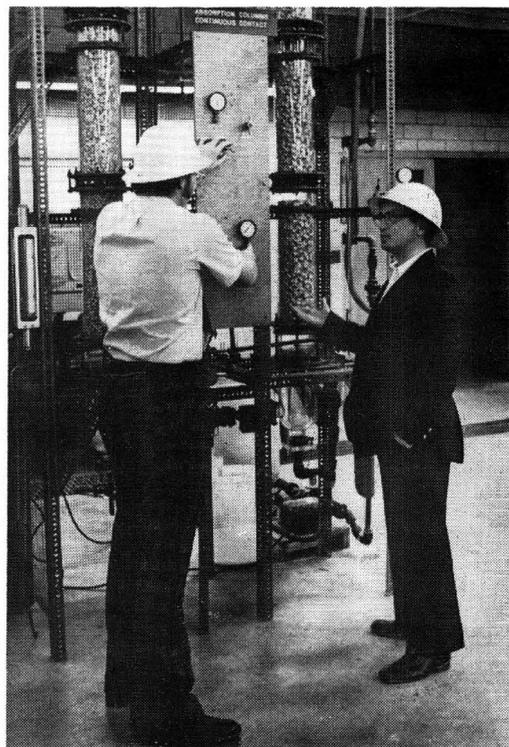
IN ADDITION TO DESIGN experience, good communications skills will be important to these students in their engineering careers. With this need in mind, the grant from the Exxon Education Foundation helped to develop another pro-

gram called "Communications Integrated Into Engineering Curriculum". Marian Jones, a journalist with a background in ChE, conducts the program to help each student develop oral and written communications skills.

Beginning in the sophomore year, Mrs. Jones schedules individual conferences with the students as they are needed, and gives each one advice for improving writing and speaking abilities. A video tape system is available to allow students to evaluate themselves in oral presentations. Students gain experience in writing laboratory reports, progress reports, memos, and the major design examinations. In addition, they are given advice in preparing resumes and job applications.

West Virginia's PRIDE program has not gone unnoticed. Representatives from industry conducting job interviews on campus have commented on the poise and self-confidence the students exhibit.

Although research is not emphasized in the undergraduate curriculum, that is not to say it has no place at WVU. When Dr. C. Y. Wen became department chairman in 1969, he brought to the job an expertise in coal/energy research. Under his direction, the department has become internationally known for its work in energy and environmental problems.

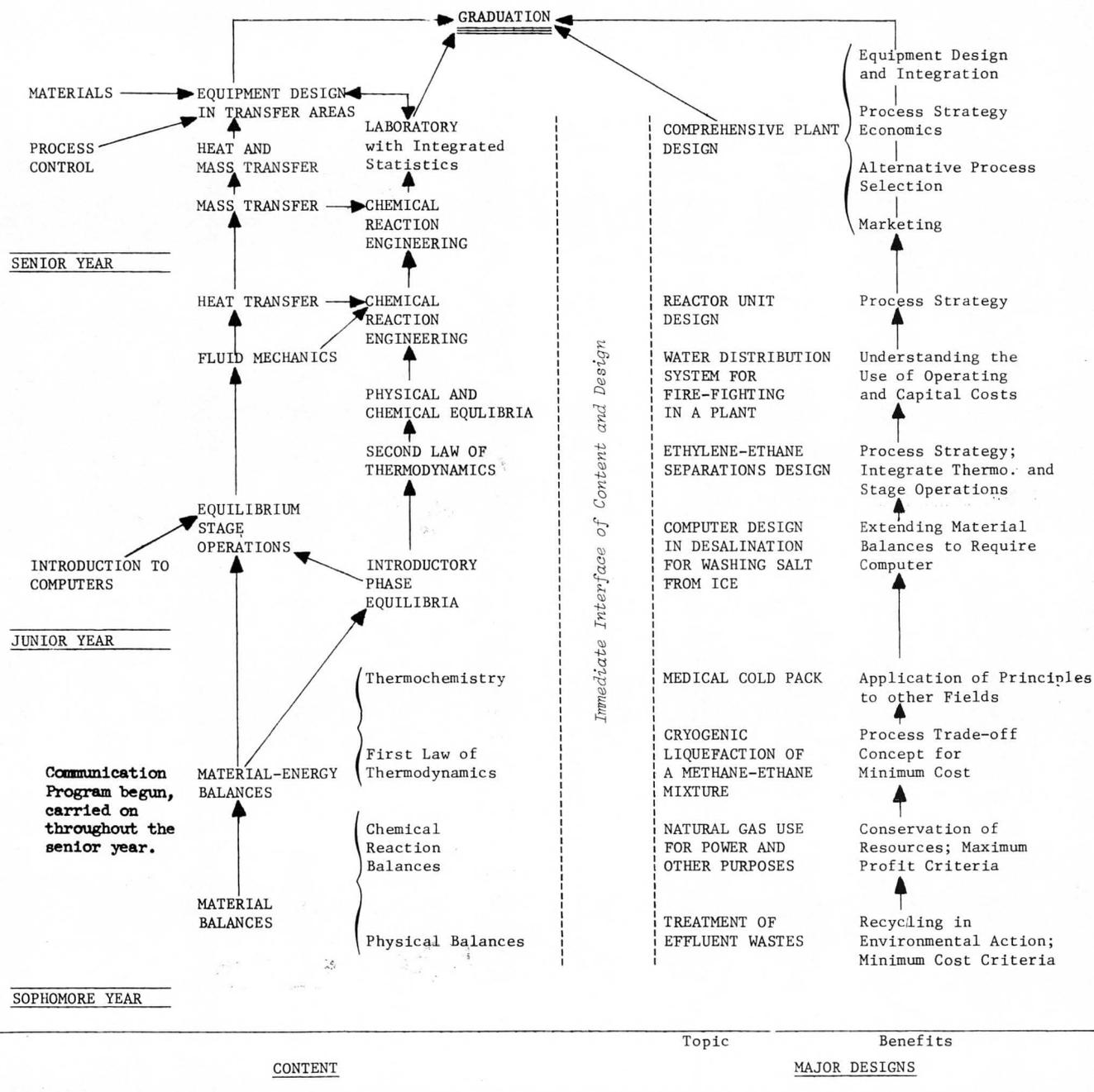


John Sears, faculty member, discusses performance characteristics of an adsorption column.

Continuing research programs in the area of coal conversion technology have gone on for several decades. Currently, one of these projects will assess the potential of coal-based energy complexes which produce either liquids, gases, power, or combinations from coal. Research is presently

being conducted on processes for reducing air and water pollution. These projects range from small scale laboratory studies determining the feasibility of electrophoretic dewatering of chemically stabilized emulsions to the design, construction, and operation of a 60,000 gallon/day reverse

Integrated Content-Design Flowsheet for West Virginia University



Simple laboratory experiments are introduced throughout the curriculum when appropriate. Content and design particulars may vary from year to year. An advantage of the use of the flowsheet is that if more, or less, time is required for student comprehension of a concept of design, the curriculum flow can be shifted. For example, Reactor Design may have a greater emphasis in the junior year for one class, for the next class it may have more emphasis in the senior year.

The PRIDE program combines individualized instruction, increased emphasis on design courses, and programmed instruction to provide Professional Reasoning with Design Experience.

osmosis pilot plant to study the possibility of producing potable water from acid mine drainage.

Extensive research is underway on novel separation processes. Joe Henry's research on dual functional separations combines the interactions of surface, electrokinetic, and diffusion phenomena to develop novel separation techniques. The relevance of these research projects is reflected by the solicitation of Henry and Wen to teach courses on New Separations and Heat Transfer in Fluidized Beds for the AIChE Today Series.

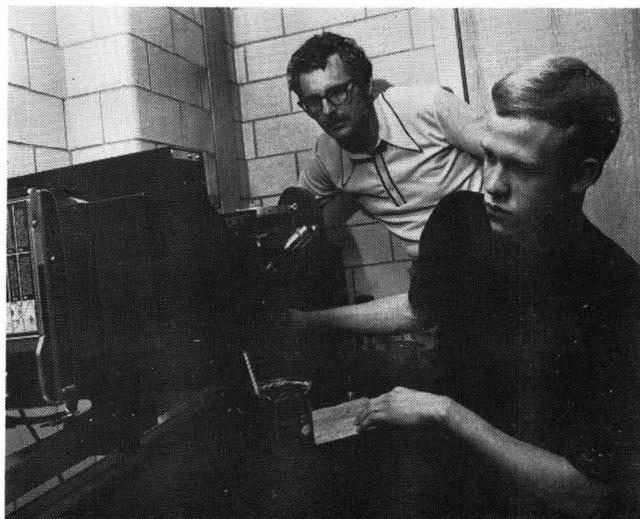
Graduate students are encouraged to take an active role in the department's research activities. Besides the M.S. Ch. E., for students who have earned a B.S. Degree in ChE, students who hold a baccalaureate degree in ChE, in other fields of engineering, or in the physical sciences may work toward the M.S.E. in a broad interdisciplinary program.

Some of the projects in which these students are involved include fluidization, materials science, separation processes, simulation, and optimization. Interdisciplinary research has also been conducted in biomedical engineering.

For the past fiscal year, \$1,200,000 in federal funds have been awarded to the College of Engineering for research in the coal/energy field. The energy research program is diverse, e.g., projects are underway on energy policy, energy farming,

and tertiary oil recovery in addition to coal conversion. Almost half of these grants were administered by the ChE faculty. In addition, grants have been received for research in such diverse areas as dual functional separations, polymer processing and biomedical engineering.

From the state's earliest days, West Virginia's mountaineers have had a reputation for bold thought and decisive action. These characteristics are reflected in the innovative curriculum and far-sighted research objectives developed by WVU's Department of Chemical Engineering. Confident of their preparation, students leave the university



Students in the PRIDE program work in laboratories with faculty supervision. Here Dr. Duane Nichols is shown with student.

to pursue their careers. Some go to work in cities and towns in all parts of the country. Others stay here to apply their technical skills to the development and implementation of the potential of West Virginia. □

ACKNOWLEDGEMENT

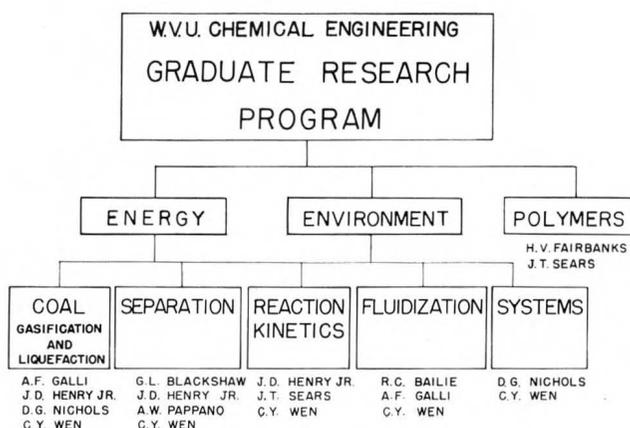
The faculty expresses its sincere thanks to Susan S. Dotson for writing this article and Marian W. Jones for her editorial work.

ChE letters

Sir:

Since it is the only one of its kind, your readers may be interested in learning of the publication of the book *Comprehending Technical Japanese*, written by E. Daub, R. B. Bird and N. Inoue and published by the University of Wisconsin Press. We hope it will be a useful teaching book and research tool for engineers and scientists.

R. Byron Bird
University of Wisconsin



SELF-INSTRUCTION IN THERMODYNAMICS

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ALTHOUGH SUBSTANTIAL attention has been focused on self-paced instruction in engineering, the majority of courses continue in the traditional form of professorial lectures. A middle path can be followed in which a portion of the material is presented in the form of "written lectures" akin to, but different from SPI. In the self-instruction (not self-paced) technique, standard lectures can be intermixed with written lectures. Students come to scheduled classes and read rather than listen. A monitor is available to answer questions. With the two lectures described in this article, there were few questions. The students appeared to understand the material. None were able to complete the entire assignment in the 1.5 hour (30 minutes) second period.

The self-instruction process represents a moderate step away from classical procedures. The advantage is that students continue to attend class and do not have to break abruptly from accustomed practice. At the same time, part of the responsibility for learning as in SPI is transferred to their shoulders. If half of the lectures in a course were given with the self-instruction system, one instructor and



Frank M. Tiller, M. D. Anderson professor of Chemical Engineering and Director of International Affairs obtained his bachelor's degree from the University of Louisville in 1937 and his PhD from the University of Cincinnati in 1946. In 1962 he was awarded a Doutor Honoris Causa by the University of Brazil. He has been a staff member at Cincinnati, Vanderbilt, Lamar Tech, and the Instituto de Oleos in Rio de Janeiro. As consultant, adviser and coordinator, his services have been rendered through a variety of organizations including the Fulbright Commission, Organization of American States, and Agency for International Development.

assistant could handle two sections with substantial savings in time of senior personnel.

The author decided to test the self-instruction technique with fundamental and presumably difficult topics, (1) first law of thermodynamic and (2) entropy. No statistical control evaluation was carried out. Informally it was learned that good students developed excellent comprehension of the subjects; and poor students performed about as expected.

The following material is exactly as presented to students except for portions which were omitted for editorial purposes.

FIRST LAW OF THERMODYNAMICS

THIS "LECTURE" IS PART of an experiment to see if it is possible to present effectively a portion of the material in EGR 234 in written rather than oral form. The topics discussed in this "lecture" are equivalent to those which would be given by the lecturer. The material represents the single most important principle in the course of thermodynamics. It is a building block for all science and engineering. It is essential that every student has a thorough mastery and understanding of the subject.

It is the object to present the underlying basis for the first law of thermodynamics also known as the law of conservation of energy. The concepts which are necessary to an understanding are as follows:

- Work and heat
- Properties and non-properties, point and path functions
- Tests for exact differentials in the form

a. $dz = Pdx + Qdy$ is exact if $\frac{\partial P}{\partial y} = \frac{\partial Q}{\partial x}$

b. $\int_c dz = 0$

Note: Line integrals formed a part of prior lectures.

BACKGROUND MATERIAL

The concept of work and quasiequilibrium processes is important to the first law. (At this point a reading assignment is given.) The authors

(of the book assigned) imply that a quasiequilibrium process is inherently frictionless. That is not true. A quasiequilibrium process can be carried out *with* as well as without friction. A body can be moved very slowly up a frictional plane. A piston moving in a heat engine could work against an internal friction generating device. Therefore, the term quasiequilibrium as used by the authors should always be accompanied by the adjective "frictionless". In general, thermodynamicists use the term "reversible process" as equivalent to the works "frictionless, quasiequilibrium process". I use the expression "frictional quasiequilibrium process" to describe a large group of operations which are not reversible.

WORK AND HEAT

THE CONCEPTS OF WORK and heat are essential to the development of the first law. Heat is a transitory phenomenon which represents the passage of "something" between bodies having different temperatures. Work is similarly another transitory phenomenon which results from mechanical, electrical, magnetic, or gravitational effects. After establishing the concept of "conservation" of the effects to be studied, work and heat will be viewed as energy in transitory passage from one body to another.

You should be clearly aware that $d'W$ is a path function. Written in the form for a frictionless, quasiequilibrium process involving only work of expansion, we have

$$d'W = pdv \quad (1)$$

W is given by the area under a curve connecting A to B. (Two paths connecting the same endpoints are presented in a figure). As the areas under the curves are different, W is a path function and not a property of the system.

As we do not as yet have variables which give Q in the form YdX , it is not so easy to show that Q is a path function. However, if we resorted to experiment we should discover that heat transferred depends upon the path.

HISTORY OF THE FIRST LAW

A HISTORICAL APPROACH to the first law is helpful in an analysis of the fundamental underpinnings. Before work could be quantized and defined, the science of mechanics had to be developed. That required an understanding of motion or the inter-relationships of mass, velocity,

and acceleration. Accurate clocks were essential to measurement, and no serious progress was possible prior to the development of accurate measurement of time. Sun dials were of no value, and water clocks offer a dubious means to satisfactory experimentation. The pendulum clock was one of

In the self-instruction (not self-paced) technique, standard lectures can be intermixed with written lectures. Students come to scheduled classes and read rather than listen. A monitor is available to answer questions.

the first instruments to permit reasonably precise measurement.

A study of falling bodies was one of the important first steps in modern mechanics with the recognition of the difference between velocity and acceleration. Out of the Galileo experiments at the Leaning Tower of Pisa came the basis for the first form of the law of conservation of energy in the form:

$$v = \sqrt{2gz} \quad (2)$$

where v is the velocity and z the distance of fall from rest. Equation (2) can be manipulated into a more general form

$$\frac{v^2}{2g} + z = \frac{v_1^2}{2g} + z_1 \quad (3)$$

Later Bernoulli modified Equation (3) for a flowing fluid and arrived at

$$\frac{p}{w} + \frac{v^2}{2g} + z = \frac{p_1}{w_1} + \frac{v_1^2}{2g} + z_1 \quad (4)$$

where p is the pressure and w the specific weight. Although different language was employed, Equation (4) represented the first law of the conservation of mechanical energy.

Simultaneously with development of mechanics, experimental studies in heat were taking place. Just as the clock was basic to mechanics, the thermometer played a similar role in the science of heat. Fahrenheit produced the first reliable mercury thermometer in the early part of the eighteenth century just as the steam engine and industrial revolution began to emerge. The thermometer permitted studies to be made in a variety of areas including irreversible mixing of hot and cold bodies. From such experiments came equations of the form

$$m_1 C_1 (T_1 - T) = m_2 C_2 (T - T_2) \quad (5)$$

where T is the final temperature and T_1 and T_2 are the initial temperatures. Equation (5) represents a form of conservation of heat energy.

The idea of "heat energy" is foreign to modern thermodynamicists. As pointed out earlier, heat is a transitory phenomenon and therefore not something which is indestructible and conserved. Nevertheless, the caloric theory of heat evolved upon the basis that heat was an imponderable (no mass) fluid which could neither be created or destroyed.

Thus, at the beginning of the nineteenth century, there were two important theoretical principles which might be referred to as:

- Conservation of mechanical energy
- Conservation of heat energy

During the first half of the nineteenth century, a basis was laid for unifying the two principles which at that time appeared to be irreconcilable to many scientists.

The principle of conservation of energy was developed on slim evidence. A highly specialized case was extrapolated into a great law. The second law of thermodynamics was established before the first law in Carnot's remarkable writings, the numbering of the laws having nothing to do with their chronological development.

A number of people contributed to the development of the first law and to the demise of the caloric theory. The problem of friction entered heavily into the debate over the energy laws. It was known that mechanical actions such as canon boring produced large amounts of heat. It was reasoned that an "imponderable" fluid was not a reasonable hypothesis. Basically it was found that the frictional work as measured by the number of turns of a frictional device was proportional to the increased length of a mercury column in a small bore tube (as shown in a figure). The turns were considered to be proportional to work and the length of the mercury column (temperature) proportional to heat absorbed by the cooling water. Stated mathematically

$$d'W \Rightarrow J d'Q \quad (6)$$

where the arrow indicates the work was converted to heat but the process (by the second law) could not be reversed. It was a one way frictional process in which mechanical energy disappeared and the cooling water became hotter.

It is interesting to note Equation (6) depends upon the straightness of the line. If the data had yielded a curve, say a parabola of the form $W = KT^2$ instead of $W = KT$, no one would have presumed there was a direct, linear relation between Q and W . If water with dye had been used as a thermometer, the results would have been drastic, near 4°C , where water has its maximum density. (A figure demonstrates the minimum length of the water column and the lack of linearity. The curve is double-valued). We can philosophize over what might have happened if the length of the mercury column had not been approximately proportional to what we call "temperature" today. Even with mercury, the expansion is not quite linear with temperature. There is no question but that the line shown would not be straight for any carefully done experiment. Nevertheless, a true spark of genius led scientists to assume Equation (6) was valid under all circumstances and to adjust the specific heat of various substances to force Equation (6) to remain valid. That has turned out to be a truly monumental "fudge factor" methodology.

On performing the reverse process of adding heat to a gas or vapor as in a steam engine, it was discovered that the work was not all changed into

Nevertheless, a true spark of genius led scientists to assume Equation 6 was valid under all circumstances and to adjust the specific heat of various substances to remain valid. That has turned out to be a truly monumental "fudge factor" methodology.

heat so that we may write

$$d'Q - d'W = dz \quad (7)$$

where dz simply represents the difference between the heat added $d'Q$ and the work of expansion $d'W$, both of which are inexact differentials. It would be quite natural to inquire about the properties of z . Is it an exact or inexact differential? If it is exact, it is a property of the system. If it is inexact, it is kin to Q and W in that it, is a path function.

If the process involved only reversible work of expansion, $d'W$ could be written as

$$d'W = pdV \quad (8)$$

and (7) would become

$$dz = d'Q - pdV \quad (9)$$

We do not know whether to write dz or $d'z$.

Before reading further, attempt to answer the following questions. Spend no more than five minutes on the questions, and then turn the page and read the commentary.

- 1) What is your opinion about the probability of dz being
- (Continued on page 140.)

CARBERRY'S ULTIMATE PAPER

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WITH THE PROBLEM of a bloated literature with us so much these days, it was encouraging to learn recently [1] that one particularly prolific contributor at least had written his last paper. The announcement was made whilst the cardinal's nephew was travelling incognito in Italy, but it is confidently rumoured that he returned from Russia with such love that he is now lost in the deeper anonymity of matrimony, thus putting a term to his publication list—at least for a time.

While he is to be congratulated on his determination to add no more to that superabundance of papers, concerning which it is frequently and truly said "the burden of them is intolerable", it would seem only proper to honor the imperishable memory of so great a publisher by giving an account of his last work. After all, Carberrry was the founder and president of the Lucrezia Borgia Society [2] and the only recipient of the University of Minnesota's prestigious Wet Test-Meter (whatever that may be) Award. The reader should be warned however that Carberrry's work is neither clear of form nor elementary of content and though the present editor hopes that his long friendship with the author will allow him to ex-cogitate the main ideas, he is well aware that his efforts are only preliminary and that the full ex-egesis will give scope to not a few PhD students.

The manuscript which has come into the editor's hands is a palimpsest, a bundle of *foliae rescriptae*. It is written in a crabbed script reminiscent of the darkest Borgia period; the paper itself, the underneath script, is indeed so illegible that the editor is forced to adopt an almost narrative style in this preliminary exposition. (The upper script is an indescribable cursive and caused the editor a great deal of confusion until he discovered that it was the game plan for an Interhall football foray, cribbed, if you please, from the little known monograph "American football—a guide for interested Scots" [3] published by the



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A. McPherson Rutherford was born 45 years ago in Strath Spey, where he grew up with a natural bent for distillation and graduated with distinction from the Glenlivet Institute later becoming chief tester of the famous Strath Spey Distillation Company. Author of "Sampling Techniques" (1957) and "Distillation Procedures" (1963), both published by the Drambuie Press, he has lately turned his talents to mediating the American sports scene to British readers in a series of books "American X — a guide for interested Y" where X = (Football, Baseball, Basketball) and Y = (Scots, Englishmen, Welshmen). Professor Rutherford is listed in Who's Who in America.

Drambuie Press in 1960. Unfortunately this provides us with no clue for dating the paper.) The text is in Italian (suggesting that it was composed at that intermediate stage of inhibition at which the language comes most naturally to him) and parts are in terza rima to which the editor's halting prose does less than justice. However the authenticity is unquestionable since under a broken-backed T-bone formation a colophon may be discerned—*apud laboratorium catalyticum nostre damensis*—a hybrid formula of doubtful latinity but known to be used by clerks of that institution.

The title, as before announced, is "Nth-order adiabatic reaction in a plate and frame filter press". The editor, innocent of such marvels as a p. and f.f.p., was relieved to find that such carnal

knowledge was unnecessary for the MS begins "Let Π be a plate and frame filter press in which the reaction $aA + bB \rightarrow j^2C$ takes place." At first blush we feel that here is a mind of hyper-Boudartian asceticism [4] at work, for not only are the chemical species abstracted but the very reactor itself has become generalized. However there may be a Titchmarshian picturesqueness [5] hidden in the symbols for reactants and their stoichiometric coefficients which are more than likely to mean "an Ancient & bountiful Bourbon". (An alternative interpretation, that relates A to Antoinette, B to bread and C to cake, fits the action of the filter but fails on historical and linguistic grounds, since A, P and B would have to be used and the attribution to Marie—A is questionable [6]). It is to be noted that the stoichiometric coefficient of the product is positive since only an electrical engineer would be guilty of the barbarism $j^2 = -1$. After this auspicious beginning the text degenerates rapidly and it is difficult to discover what value or values of N the author had in mind. It appears that a cake gets plastered in or on Π and rapidly builds up to such a thickness that N becomes $\frac{1}{2}(N + 1)$ with dire consequences. The reaction is exothermic so that the cake is baked in situ and in the experi-

mental section there is a record of one run (an assistant K. Alfred was in charge) which ran away to such high temperatures that Π was ruined and had to be thrown out. Carberry evidently believes that gamma radiation will fix this—or at least fix Alfred.

There are several other esoteric effects that Carberry considers in his terse and lapidary style and it is with mingled emotions that we recall that this is to be his last paper. It is perhaps proof of the proof of the reactants that he finally lumps together many of these—diffusional intrusions, monoliths, filter cloths, something called naphthalene, inverse kinetics, carbon monoxide and much more—and uses his poet's license to dismiss them:

Non ragioniam di lor, ma guarda, e passa.

(Let us not speak of them, but look and pass on). □

REFERENCES

1. Chem. Eng. Educ. 8, 2 (1974).
2. Chemtech. Feb. 1974, p. 124.
3. Who's Who. 1974-75 Edn. 2, 2672.
4. Boudart, M. Kinetics of chemical processes. Prentice-Hall. 1968. p.v.
5. Titchmarsh, E. C. Introduction to the theory of Fourier integrals. Clarendon Press. 1937. p.v.
6. Oxford Dictionary of Quotations. 2nd Edn. 329:18.

The Short Happy Life of Aris Rutherford*

It pops up on page 2,672 of the current edition of "Who's Who in America," a thirteen-line biography set between those of James Merle Ruth ("food co. exec.") and David Ross Rutherford Jr. ("educator"). The luminary is Aris MacPherson Rutherford, a Scottish-born professor who graduated from the "Strath Spey and Glenlivet Institute of Distillation Engineering," is a trustee of the "Scottish-Greek Friendship Foundation" and has written a book called "American Football: A Guide for Interested Scots."

Aris MacPherson Rutherford is also a phony. For the first time in its 78-year history, "Who's Who," that fusty arbiter of American celebrity, has been victimized by a hoaxer. The confessed perpetrator is Rutherford Aris, 45, a normally nonsensical professor of chemical engineering at the University of Minnesota. A while back, Aris, who was already listed in "Who's Who," received a biographical form from the reference book's publisher addressed to "Aris Rutherford." Aris assumed correctly that the name transposition was a computer error and let it pass, but a rather pompously insistent follow-up letter convinced

him that "Who's Who" was "begging to have its leg pulled." Since Aris Rutherford sounded Scottish, the professor meshed the fictional specialty of "distillation engineering" with the name of Glenlivet, a label familiar to lovers of unblended malt whisky.

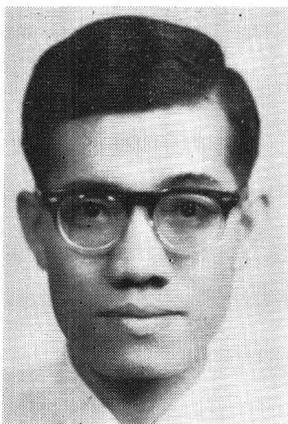
This is not the first time that the 70,000-odd entries in "Who's Who" have included a fake. In order to discover those who use "Who's Who" as a source for mailing lists, the book's Chicago-based publishing firm occasionally inserts bogus biographies using employees' home addresses. "But I know of no other instance," sighs Kenneth Petchenick, the firm's president, "where a made-up biography has gotten in from the outside." After The Minneapolis Star exposed the hoax, Aris sent an apologetic letter to Petchenick, although he had already submitted an update on Rutherford's record to include the title of his latest book: "American Baseball: A Guide for Interested Englishmen."

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TRANSIENTS IN PLUG FLOW SYSTEMS

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THE PLUG FLOW MODEL, along with the completely stirred tank model, may be one of the most basic or elementary flow models in chemical engineering. This is hardly surprising because of the tubular nature of many of the equipment employed in a variety of continuous chemical systems and processes such as chemical reactors, heat exchangers, gas adsorption, extraction, and adsorption. Many steady state design equations for these processes are based on the plug flow model (e.g. see Perry and Chilton, 1973).



S. H. Lin was born in Kaohsiung, Formosa on September 7, 1940. He received the B. S. degree from Chung Yuan College in 1965, the M. S. degree from National Taiwan University in 1968 and the Ph. D. degree from Kansas State University in 1974.

From 1968 to 1970 he was an instructor at the Department of Chemical Engineering, Chung Yuan College. He is currently a lecturer in the Department of ChE., University of Melbourne, Australia participating in research and teaching activities in water pollution control and biochemical engineering.

L. T. Fan was born in Formosa on August 7, 1929. He received the BS degree in ChE. from the National Taiwan University in 1951, the MS degree in ChE. from Kansas State University in 1954, and PhD degree in ChE. from West Virginia University, Morgantown, in 1958. In that same year he joined the faculty of Kansas State University, where he is now Professor and Head of Chemical Engineering, and Director of the Institute for Systems Design and Optimization. He has published two books and numerous technical papers in chemical reaction engineering, environmental pollution control, energy resource conversion, systems engineering, fluidization, and related fields.

These processes as well as other chemical processes, are often operated under transient or unsteady conditions during start-up and shut-down. They are also constantly subject to environmental disturbances and changes in feed conditions.

It appears that, in spite of its importance, the elementary analysis of transient characteristics of processes represented by the plug flow model has seen only limited coverage in undergraduate textbooks in process dynamics and control, reaction engineering, transport phenomena, and process design. This contrasts sharply to the situation for processes described by the completely stirred tank model.

The deterministic mathematical representation of a plug flow process under transient conditions is a first order, one-dimensional partial differential equation (hyperbolic PDE) or a set of such equations. This note contains tutorial material for solution of a first order partial differential equation by means of a well-known technique, namely the method of characteristics (Abbott, 1966; Acrivos, 1956; Aris and Amundson, 1973; Courant, 1962; Lapidus, 1962; Liu, Aris, and Amundson, 1962), which is suitable for presentation to undergraduate classes.

BASIC PRINCIPLE

THE GENERAL EXPRESSION for a first-order, one-dimensional partial differential equation can be written as

$$A(T, t, x) \frac{\partial T}{\partial t} + B(T, t, x) \frac{\partial T}{\partial x} = R(T, t, x) \quad (1)$$

subject to

$$T = T_0(x) \text{ at } t = 0, x \geq 0 \quad (2)$$

$$T = T_1(t) \text{ at } t > 0, x = 0 \quad (3)$$

in which T denotes the dependent variable, t the time variable, x the space variable, and $R(T, t, x)$ the source or sink term. $A(T, t, x)$ and $B(T, t, x)$ represent arbitrary functions of T , t and x or a constant,

As indicated by Eq. (1), the solution for T can be expressed in terms of t and x ; hence, the total differential of T can be written as

$$\frac{\partial T}{\partial t} dt + \frac{\partial T}{\partial x} dx = dT \quad (4)$$

Since the solution of Eq. (1) should also satisfy Eq. (4), there exists a parameter α such that $A(T,t,x) = \alpha dt$, $B(T,t,x) = \alpha dx$, $R(T,t,x) = \alpha dT$ or

$$\frac{dt}{A(T,t,x)} = \frac{dx}{B(T,t,x)} = \frac{dT}{R(T,t,x)} = \frac{1}{\alpha} \quad (5)$$

Equation (5) can be rewritten as

$$\frac{dx}{dt} = \frac{B(T,t,x)}{A(T,t,x)} \quad (6)$$

and

$$\frac{dT}{dt} = \frac{R(T,t,x)}{A(T,t,x)} \quad (7)$$

Equations (6) and (7) should satisfy the conditions given by Eqs. (2) and (3).

The original partial differential equation, Eq. (1), now is transformed into two ordinary differential equations, Eqs. (6) and (7). The first, Eq. (6), represents the so-called characteristic lines along which the second, Eq. (7), is integrated. Both Eqs. (6) and (7) can be integrated either analytically or numerically. It should be noted that a set of these two equations is not an approximation to the original partial differential equation. However, approximate or exact solutions can be obtained for these two equations depending on their complexities.

The integration of Eqs. (6) and (7) subject to the appropriate conditions can be graphically interpreted by Fig. 1. In this figure, the independent variables, t and x , are chosen as two coordinates, and the magnitude of T , if shown, will appear as a line segment perpendicular to the $(t-x)$ plane. The curves, i.e., characteristic lines, originating from the t -axis or the x -axis represent the $(t-x)$ relation determined by integrating Eq. (6). The characteristic line passing through the origin divides the $(t-x)$ plane into two regions: the upper left region, and the lower right region. In the upper left region the dependent variable, T , can be obtained by integrating Eq. (7) and by using the condition given by Eq. (3). Therefore, starting from a certain point on the t -axis, the values T can be determined for every point along the corresponding characteristic line. Similarly the values of T on the lower right region can be obtained by integrating Eq. (7) with the condition given by Eq. (2). Note that there exists a discontinuity in the

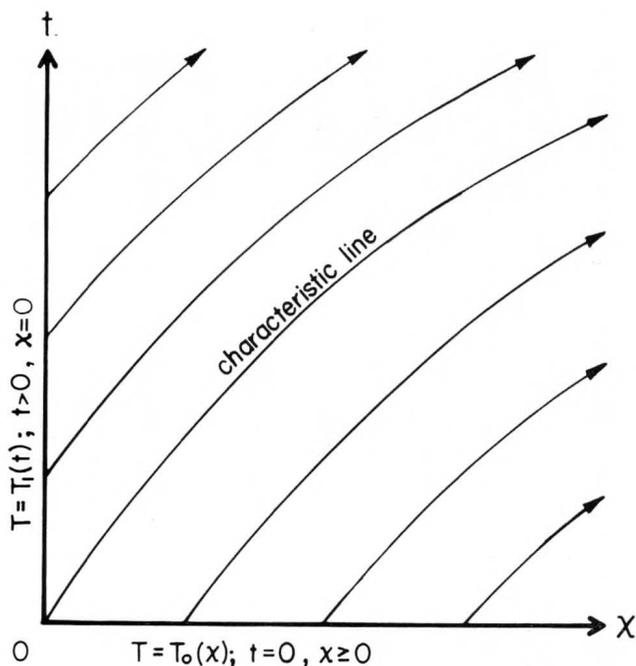


FIGURE 1. Representation of the characteristic lines in the $(t-x)$ plane.

values of T along the characteristic line passing the origin if $T_1(0) \neq T_0(0)$.

The characteristic lines shown in Fig. 1 are projections down from the three-dimensional space. They are plotted parallel to each other in this figure for clarity. In reality, the characteristic lines may not be so simple especially when A and B are strongly nonlinear functions of T , t , and x . They may become twisted as the value of T changes, and projections of them down from the three dimensional space to the $(t-x)$ plane may lead to their crossing.

EXAMPLES

TWO EXAMPLES ARE GIVEN here for illustration. Consider the linear partial differentiation equation

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} = -kC \quad (8)$$

subject to

$$C = 0 \text{ at } t = 0, x \geq 0 \quad (9)$$

$$C = C_0 \text{ at } t > 0, x = 0 \quad (10)$$

Equation (8) represents the start-up of an isothermal plug flow reactor, with a first order chemical reaction. The reactor contains no reactant initially and is then fed with a reactant with a fixed concentration of C_0 . In reality, performance equations of numerous processes such as ion exchange, gas adsorption and heat transfer which take place in a long tubular system can be

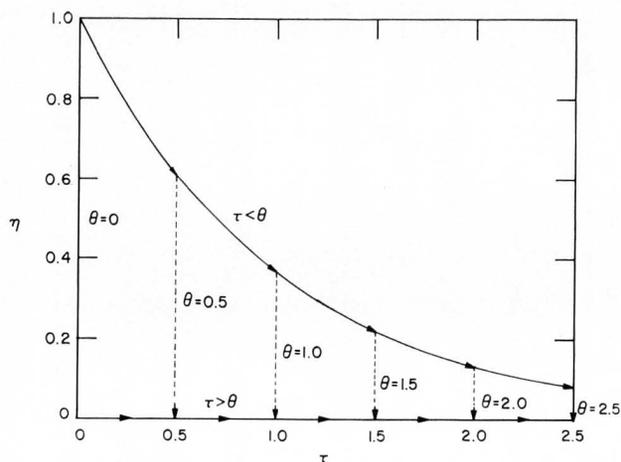


FIGURE 2. Concentration vs. distance for the first example.

transformed into the form represented by Eq. (8) by simple linear transformation.

For simplicity, the following dimensionless groups* are introduced:

$$\eta = \frac{C}{C_0}, \theta = kt, \tau = \frac{xk}{U}$$

Then Eqs. (8), (9) and (10) can be rewritten as

$$\frac{\partial \eta}{\partial \theta} + \frac{\partial \eta}{\partial \tau} = -\eta \quad (11)$$

subject to

$$\eta = 0 \text{ at } \theta = 0, \tau \geq 0 \quad (12)$$

$$\eta = 1 \text{ at } \theta > 0, \tau = 0 \quad (13)$$

According to Eq. (5), one can write

$$\frac{d\theta}{1} = \frac{d\tau}{1} = \frac{d\eta}{-\eta} \quad (14)$$

This expression can be rewritten into the following two parts;

$$\frac{d\tau}{d\theta} = 1 \text{ with } \theta \geq 0, \tau \geq 0 \quad (15)$$

and

$$\frac{d\eta}{d\tau} = -\eta \quad (16)$$

$$\eta = \frac{C}{C_0}, \theta = kt, l = \frac{x}{L}$$

with

$$\eta = 0 \text{ at } \theta = 0, \tau \geq 0 \quad (17)$$

*The dimensionless groups used here are not necessarily unique. For example, the following dimensionless groups can also be employed in many cases.

$$\eta = 1 \text{ at } \theta > 0, \tau = 0 \quad (18)$$

Integration of Eqs. (15) and (16) yields, respectively,

$$\tau = \theta + \Delta\theta \quad (19)$$

$$\eta = Ae^{-\tau} \quad (20)$$

where $\Delta\theta$ and A are integration constants to be determined.

For the condition of $\theta = 0$ and $\tau \geq 0$ which appears in Eq. (17), Eq. (19) gives

$$\Delta\theta \geq 0$$

which implies that

$$\tau \geq \theta$$

because $\tau = \theta + \Delta\theta$. Therefore, the solution obtained by using the condition of Eq. (17) is applicable when $\tau \geq \theta$. Thus from Eq. (20), one obtains $A = 0$ and

$$\eta = 0, \tau \geq \theta \quad (21)$$

Similarly, for the condition of $\theta > 0$ and $\tau = 0$, which appears in Eq. (18), Eq. (19) gives

$$\Delta\theta < 0$$

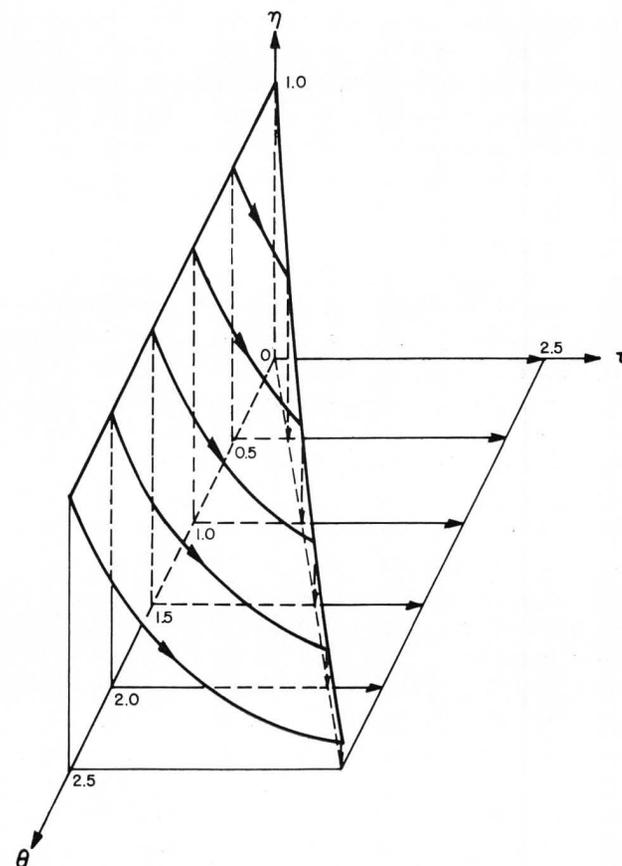


FIGURE 3. Three-dimensional concentration plot for the first example.

which is equivalent to

$$\tau < \theta$$

because $\tau = \theta + \Delta\theta$. Hence, the solution obtained by using the condition, Eq. (18), is valid in the region $\tau < \theta$. The solution obtained by applying Eq. (18) to Eq. (20) is

$$\eta = e^{-\tau}, \tau < \theta \quad (22)$$

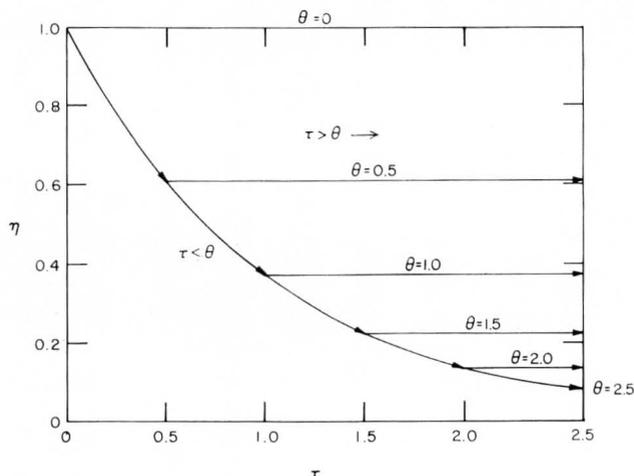


FIGURE 4. Concentration vs. distance for the second example.

Equations (21) and (22) constitute the complete solution of Eq. (11) subject to Eqs. (12) and (13).

Figures 2 and 3, respectively, show the two- and three-dimensional concentration distributions. It can be seen in Fig. 3 that there is a discontinuity in the concentration surface along the characteristic line passing the origin.

Consider a second example which is governed by the same partial differential equation, Eq. (11), but subject to the following conditions;

$$C = C_0 \text{ at } t = 0, x \geq 0, \text{ or } \eta = 1 \text{ at } \theta = 0, \tau \geq 0 \quad (23)$$

$$C = C_0 \text{ at } t > 0, x = 0, \text{ or } \eta = 1 \text{ at } \theta > 0, \tau = 0 \quad (24)$$

These conditions imply that the reactor is originally filled with a reactant having the concentration of the feed. Obviously, Eqs. (19) and (20) are still applicable.

From Eqs. (19), (20) and (23), one has

$$\tau \geq \theta$$

and

$$1 = A e^{-\Delta\theta} \quad (25)$$

(Continued on page 148.)

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EXPERIMENTS IN HETEROGENEOUS CATALYSIS: Kinetics of Alcohol Dehydration Reactions

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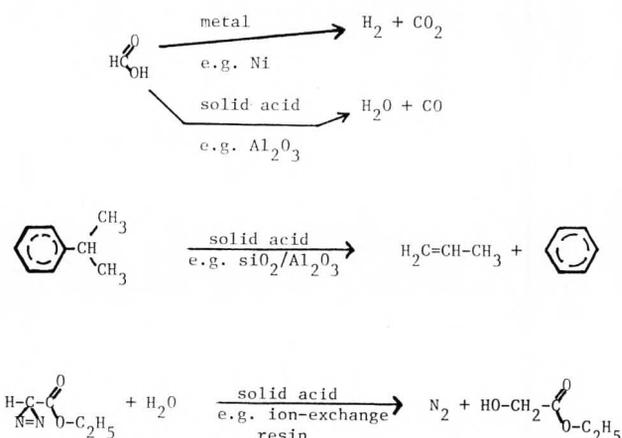
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IN MANY INDUSTRIAL chemical processes, the reactions are catalytic, taking place on internal surfaces of high-area porous solids. The chemical nature of surface catalytic sites is difficult to determine, and consequently an industrial catalyst is chosen not from understanding of reaction mechanism, but from results of trial-and-error experiments designed to determine the solid having the best combination of catalytic activity (measured by reaction rate), selectivity (measured by product distribution), and stability (measured by rate of decay of activity and selectivity during operation). Potential catalysts are often evaluated in continuous flow reactors at conditions approximating those of industrial operation. Products flowing from test reactors can be analyzed efficiently by such methods as gas chromatography or mass spectrometry, and tests may be designed to establish from product analyses the influence of temperature, pressure, and reactant composition on catalyst activity, selectivity, and stability.

Before the development of analytical methods like gas chromatography allowed efficient evaluation of catalyst performance, there was little quantitative data available. Early researchers in catalysis recognized the advantages of experiments that could be interpreted without the need for frequent product analyses, and consequently some of the most thorough investigations concerned reactions of model compounds which give gaseous products and allow rates of reaction to be measured as rates of gas evolution. For example, the following decomposition reactions have been

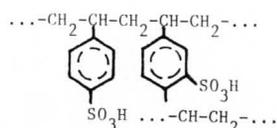
studied extensively to characterize catalysis by solid acids and by metals [1, 2, 3]:



Reactions in this class are no longer objects of much research, but they retain their value as easily accessible means for study of heterogeneous catalysis, a practically important subject which is usually neglected in undergraduate laboratories. Our objective is to point out a heterogeneously catalyzed reaction, the dehydration of *t*-butyl alcohol to give isobutene, which can be investigated in a simple, inexpensive, and safe experiment; yielding thorough kinetic data in a short time. One of the recommended catalysts is an ion-exchange resin, which is applied industrially to catalyze the hydration of propylene to give isopropyl alcohol [4].

EXPERIMENTAL METHODS

TERTIARY-BUTYL ALCOHOL at its boiling point (82.5°C) undergoes no decomposition reaction, but in the presence of an acid such as a sulfonated copolymer of styrene and divinylbenzene (an ion-exchange resin),



a decomposition reaction proceeds rapidly, giving water and isobutene gas [5]. The rate of isobutene evolution can be measured easily with a soap-film flow meter or a wet-test flow meter. When this rate is measured with the equipment shown in Figure 1, the reaction rate can be measured as a function of alcohol concentration in solution with methylcyclohexane (expected to be an inert diluent) and as a function of alcohol concentration in solution with water (a reaction inhibitor). Methylcyclohexane and water have been chosen because each forms an azeotrope with *t*-butyl alcohol at about 78°C; a range of solution compositions, all boiling at nearly the same temperature, can therefore be studied—and the reactants themselves provide a thermostat.

In the suggested experiment, a series of methylcyclohexane-*t*-butyl alcohol solutions is prepared, and each is stored over particles of activated Linde 4A Molecular Sieve to remove impurity water. In a kinetics experiment, 200 ml of solution are charged to the reaction flask and brought to a boil. A weighed sample of ion-exchange resin catalyst beads (Amberlyst 15, Rohm and Haas) is transferred rapidly to the reactor from a vacuum oven at 120°C, where it has been

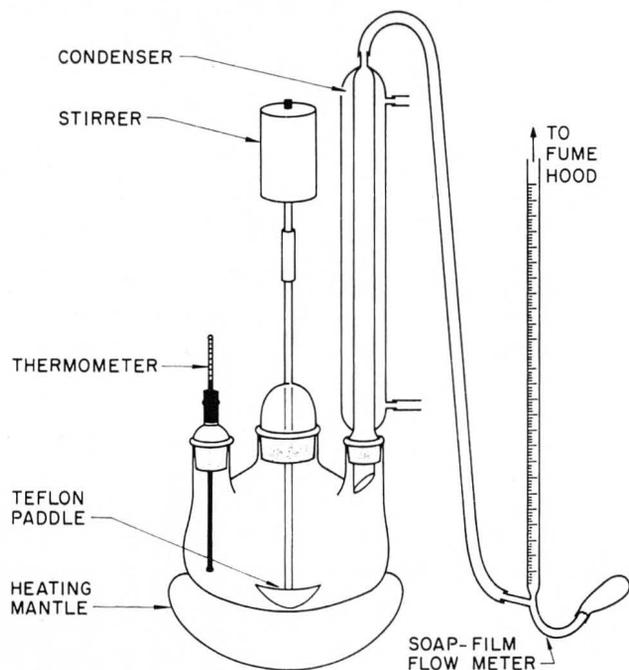


FIGURE 1. Apparatus for Measurement of *t*-Butyl Alcohol Dehydration Kinetics.

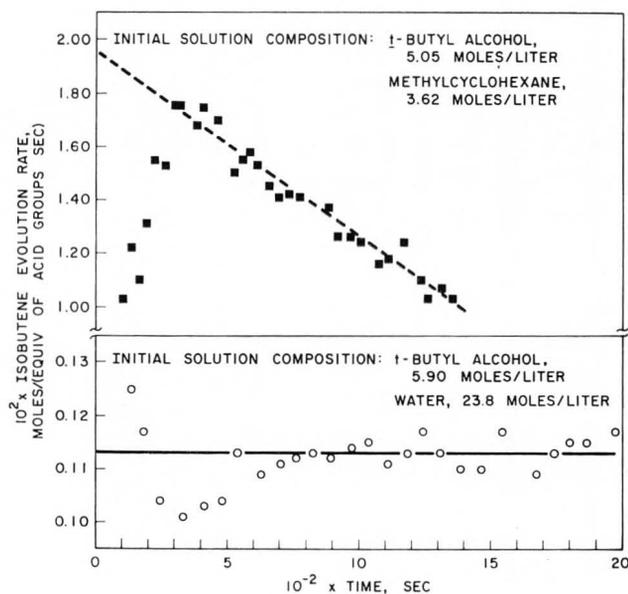


FIGURE 2. Rates of *t*-Butyl Alcohol Dehydration (8).

dried overnight. The rate of evolution of isobutene is then measured periodically, about once per minute, for half an hour. Typical results (Figure 2) indicate a rapidly increasing rate of evolution as the solution becomes saturated with isobutene. After saturation, the rate of evolution becomes equal to the rate of reaction, which decreases with time as water accumulates in the reactor and inhibits reaction. The reaction rate characteristic of the initial solution composition is determined by extrapolation of the reaction rate data to zero time (Figure 2). Rate is determined for various stirring speeds and amounts of catalyst in the reactor, and when there is no effect of either variable on rate per equivalent of catalyst $-\text{SO}_3$ groups, determined by titration (ref. 6, pp. 91-92), the reaction is free of the influence of mass transfer in the liquid phase, and intrinsic chemical kinetics are determined [7].

Data for water-alcohol solutions are obtained in a similar way; the procedure is simpler when the water concentration is high. Then as illustrated by the data of Figure 2, the solution becomes saturated rapidly with isobutene, and after data are collected for a few minutes, a known amount of water is added to the reactor and the procedure is repeated for the new solution composition.

RESULTS

A SET OF RATE DATA is shown in Figure 3 [8]. These results demonstrate kinetics common to many reactions catalyzed by surfaces and

enzymes: The data represented by the dashed line show that the reaction is approximately first order in reactant concentration at the lowest values, approaching zero order at high values as the catalytic sites (sulfonic acid groups) become saturated with reactant. The data represented by the solid line show that water present at the lowest concentrations is a strong inhibitor, competing with alcohol for the catalytic sites. When water is present in high concentrations, it is no longer an inhibitor (inset, Figure 3); the resin becomes strongly hydrated and similar to an aqueous solution of dissociated acid; the reaction is catalyzed by hydronium ions and is first order in reactant concentration.

An interpretation of the catalyst structure and reaction mechanism is given elsewhere with an empirical rate equation [8]. Determination of a non-linear rate equation to fit the data is easily accomplished with the least-squares algorithm of Marquardt [9], which is a standard program available at many computer centers.

EXTENSIONS OF THE EXPERIMENT

THE ADVANTAGES OF THIS experiment are the ease of production of kinetic data and the many possibilities for modification and extension. Most of the modifications suggested in the following paragraphs have been investigated by students in freshman research seminars at the University of Delaware and Massachusetts Institute of Technology.

Catalysts—The resin catalyst can be modified easily by ion exchange, as sulfonic acid groups are replaced by their salts.* Replacement of acid groups markedly reduces catalytic activity [10]. The reaction is also catalyzed by many other insoluble acids, including commercial zeolite crack-

Our objective is to point out a reaction, the dehydration of *t*-butyl alcohol, to give isobutene, which can be investigated in a simple, inexpensive and safe experiment; yielding thorough kinetic data for a heterogeneously catalyzed reaction.

*The process of ion exchange is widely applied in water purification, and this application of the resins is industrially much more important than catalytic applications [9].

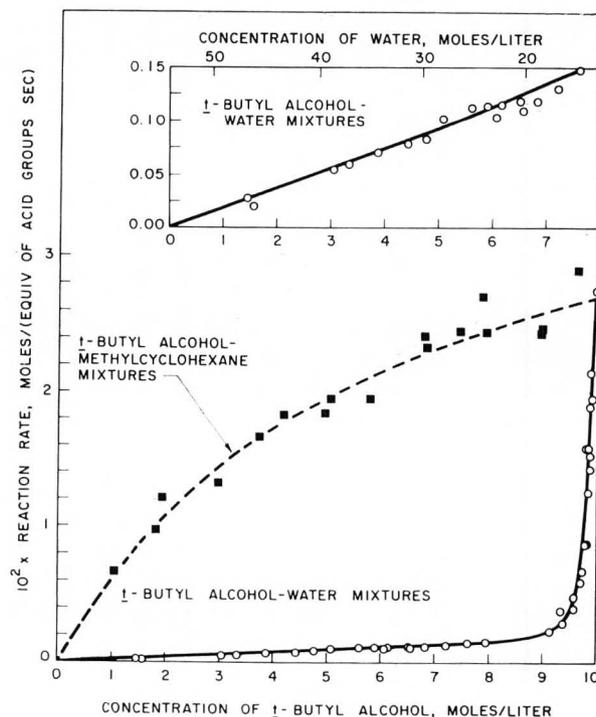


FIGURE 3. Kinetics of *t*-Butyl Alcohol Dehydration Catalyzed by Sulfonic Acid Ion-Exchange Resin at $80 \pm 2^\circ\text{C}$ (8).

ing catalysts (used in gasoline manufacture) and the zeolite H-mordenite [11]. The zeolites have only about 1% of the activity of the sulfonic acid resin per unit mass of catalyst. Soluble acids such as *p*-toluenesulfonic acid** and polystyrenesulfonic acid (analogs of the resin) can also be used.

Reactions—Other alcohols, e.g. *s*-butyl alcohol, undergo dehydration reactions to give olefins in the presence of the resin catalyst. Reaction of *s*-butyl alcohol at its normal boiling point (99.5°C) proceeds at only about 0.2% of the rate observed for *t*-butyl alcohol at its normal boiling point.

Decomposition reactions giving carbon monoxide from formic acid and from methyl and ethyl formates have also been investigated with the resin catalyst [13].

Reactor Design—A modified glass reactor shown in Figure 4 (a Schwab reactor) has been used for determining rates of reaction occurring as vapor-phase reactants flow at steady state through a bed of catalyst particles. Analysis of the reactor performance has been described by

**The anhydrous acid can be prepared from the commercially available monohydrate by drying under high vacuum at 40°C for 130 hours [12].

Weisz and Prater [2]. This reactor has a separately heated catalyst section, allowing study of reaction at various temperatures.

The reactor is suited to all the reactants and catalysts mentioned in the preceding paragraphs. If *s*-butyl alcohol is used as the reactant, then the gas produced in the resin-catalyzed reaction is butene-1 plus *cis*- and *trans*-2-butenes; the selectivity can therefore be studied as a function of temperature and alcohol and water partial pressures [14], provided an instrument such as a gas chromatograph is available for product analysis.

Since the resin catalyst undergoes desulfonation and loss of catalytic activity during operation at temperatures higher than about 130°C, this reactor also provides an opportunity for evaluation of catalyst stability.

Mass Transfer—Mass transfer effects in catalyst particles have been observed with ion-exchange resins like Dowex 50W-X12. This is a nonporous gel-form resin distinct from Amberlyst 15, which is a porous solid with a high internal surface area, and the interior acid groups of the gel are inaccessible to reactant alcohol

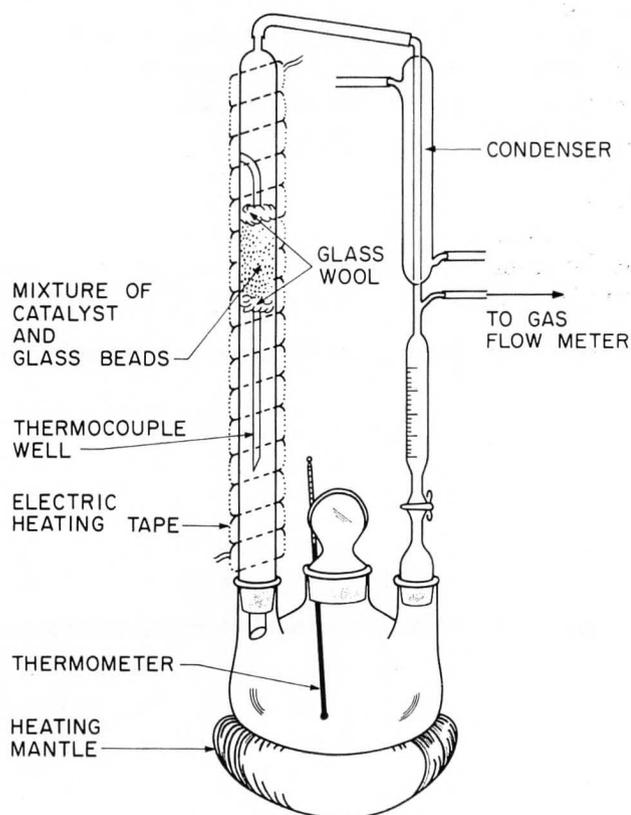


FIGURE 4. Schwab Reactor for Measurement of Reaction Rates with Vapor-Phase Reactants flowing through a Bed of Solid Catalyst Particles.

Bruce Gates has degrees in ChE from Berkeley and the University of Washington. He worked on petroleum process development at Chevron Research Company, and since 1969 he has been at the University of Delaware. His research in applied catalysis is focused on hydroprocessing of fossil fuels and on the design and characterization of polymeric catalysts incorporating acidic, basic, and metal groups.

John Sherman studied ChE at RPI and MIT and was a member of the MIT faculty from 1962 until 1966. He later worked on development of catalyst carriers and zeolites for the Norton Company in Worcester, Massachusetts. Since 1969 he has been with the Linde Division of Union Carbide in Tarrytown, New York, where, as a supervisor in the Molecular Sieve Department, he is involved in developing new products for adsorption and ion exchange.

until water is present to hydrate and swell the resin and allow passage of alcohol molecules between the polymer strands. The performance of gel-form catalysts depends strongly on particle size, crosslinking (divinylbenzene content), and water content, and the effects can be measured with the apparatus shown in Figure 1 [6].

The operation of each reactor can also be modified by inclusion of a desiccant such as Linde 4A Molecular Sieve, which selectively adsorbs water produced in reaction and reduces the product inhibition as reaction proceeds. □

REFERENCES

1. Mars, P., Scholten, J. J. F., and Zwietering, P., *Advan. Catal.* 14, 35 (1963).
2. Weisz, P. B., and Prater, C. D., *Advan. Catal.* 6, 143 (1954).
3. Gruber, P. E., and Noller, H., *Z. Phys. Chem. (Frankfurt)*, 41, 353 (1964).
4. Neier, W., and Woellner, J., *Chem. Technol.*, 95, February, 1973.
5. Frilette, V. J., Mower, E. B., and Rubin, M. K., *J. Catal.* 3, 25 (1964).
6. Helfferich, F., "Ion Exchange," McGraw-Hill, New York, 1962.
7. Heath, H. W., Jr., and Gates, B. C., *Amer. Inst. Chem. Eng. J.* 18, 321 (1972).
8. Gates, B. C., and Rodriguez, W., *J. Catal.* 31, 27 (1973).
9. Marquardt, D. W., *J. Soc. Ind. Appl. Math.* 11, 431 (1963).
10. Gates, B. C., Wisnouskas, J. S., and Heath, H. W., Jr., *J. Catal.* 24, 320 (1972).
11. Ignace, J. W., and Gates, B. C., *J. Catal.* 29, 292 (1973).
12. Zundel, G., "Hydration and Intermolecular Interaction. Infrared Investigations with Polyelectrolyte Membranes," p. 129, Academic Press, New York, 1969.
13. Knözinger, E., and Noller, H., *Z. Phys. Chem. (Frankfurt)*, 79, 66 (1972).
14. Thornton, R., and Gates, B. C., *J. Catal.*, in press.

POLLUTION OF THE ENVIRONMENT- CAUSES AND CURES

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DURING THE FALL of 1972 the Chemical Engineering Faculty at Michigan State University (MSU) deliberated on the idea of offering a course to the general university student body. These considerations were motivated to some extent by discussions by College of Engineering administrators at Michigan State University of the desirability and the challenge related to such an undertaking. These two factors, in turn, were based primarily on cost accounting methods used by the university and an opportunity to participate in general education. Courses were beginning to be offered by various departments and colleges on ecology and other topics related to environmental issues. We asked ourselves at that time questions such as:

"What unique subjects related to the environment could the Chemical Engineering faculty offer to the University?" and "Should we really try to develop a course of general interest?"

During this same period Dr. Hawley was working with Dr. R. J. Foresti of Catholic University on the development of a session for the Chemical Engineering Division program of the 1973 Annual Meeting of ASEE at Iowa State University on the subject of "Courses by ChE Faculty for Non-Engineering Students." Dr. Foresti had developed and taught a course on pollution for the general student body and provided us with valuable assistance and encouragement during this early planning period. Finally, late in the Fall of 1972, the ChE faculty at MSU decided it was qualified to teach a general course on pollution of the environ-

ment. It was our observation that many environmental courses on a number of campuses were treating, to a large extent, only the effects of pollution on the environment and were not dealing with the total picture as related to the causes and cures of pollution. We recognized that offering such a course to the university community represented an expansion of the scope of ChE and engineering education at MSU. This matter was discussed with Dean L. W. Von Tersch, and he encouraged the ChE Department to develop the course. Finally, normal channels were pursued to obtain course approval.

An outline for a course entitled "Pollution of the Environment—Causes and Cures" was quickly developed by Dr. C. M. Cooper, approved by the ChE faculty, and submitted to the College of Engineering Curriculum Committee on November 21, 1972. It was here that this new course met its first major roadblock. The primary issue was that each of the other departments questioned whether ChE was truly qualified to teach this pollution course;

It was our observation that many environmental courses . . . were treating, to a large extent, only effects of pollution . . . and were not dealing with the total picture as related to the causes and cures of pollution . . . Offering such a course . . . represented an expansion of the scope of ChE at MSU.

when in fact chemical engineers, with their processing and chemical background, are truly "naturals" for teaching and handling environmental problems.

After considerable delay, the course was finally approved on October 11, 1973, nearly one year after submission. It is apparent, in retrospect, that we had failed to communicate to the Curriculum

Committee that this was a general course for non-engineering students and did not really infringe on other departmental provinces. We were encouraged by the Provost's Office to continue to pursue course approval at the university level, and within a short period of time this new course was approved by both the special university Ad Hoc Committee on Environmental Courses and the university Curriculum Committee. After approval by all parties concerned, the real work of course planning and organizing began in order to offer "Pollution of the Environment—Causes and Cures" to MSU students during Spring term 1974. We began to make decisions immediately and to work on course format, assignment of lecture topics, specific course schedule, publicity, advertisements, et cetera.

COURSE OBJECTIVES

OUR PRIMARY OBJECTIVE in offering this course was to contribute in a significant manner, based on unique faculty expertise, to the environmental education program at MSU so that the decision-makers of the future will be more widely informed in their roles of solving complex energy and environmental problems. Topics on energy were included since energy conversion, consumption, and availability are all directly related to pollution and environmental degradation. It is the feeling of the ChE faculty at MSU that ChE faculty, in general, have both the educational background and experience required to effectively deal with environmental and energy problems; and hence, must interact with other sectors of our society involved in decision-making.

It was decided to treat the subject of "Pollution of the Environment—Causes and Cures" in a descriptive, but objective, fashion so that students would be familiar with the nature of causes of and approaches to solving environmental problems. Thus, it was necessary to provide students with factual information on the several sources of pollution and environmental degradation followed by a description and an objective assessment (including economics) of the alternative solutions. In this manner we were able to define the role of technology in solving problems of the environment. In order to give balance to the course, it was decided to invite speakers with various backgrounds to describe the roles of other important decision-making groups in solving problems of the environment. Arrangements were made to have prominent off-campus lecturers present their

views and knowledge of the roles of the public, government, and industry in combating problems of the environment.

It can be seen in the course outline, Table 1, that the general theme of the role of technology is implicit in the sense that the course was offered by

Our primary objective . . . was to contribute . . . based on unique faculty expertise, to the environmental education program at MSU so the decision-makers of the future will be more informed . . . in solving complex energy and environmental problems.

the ChE Department and taught to a large extent by our faculty. The course focused on causes and cures of environmental and energy problems and included talks on the roles of industry, government, and the public in solving such problems.

PUBLICIZING THE COURSE

CONSIDERABLE EFFORT and long-range planning were required to insure the success of this new course. Further, we recognized it would be necessary to present this course to a large number of students in order to make this endeavor really worthwhile. The nature of the course concept was such that a large lecture approach could be effective if lectures were adequately organized for content and interest. We knew organization and development of general lectures would be a major task since, traditionally, ChE faculty are accustomed to small classroom, problem solving formats. Development of a good publicity program was essential to attract a large number of students. Thus, over the Christmas holiday period, the top priority items were to line up a few nationally known individuals for lectures and to develop appropriate publicity material for newspapers, radio, and mail campaigns. Students at MSU pre-enroll for courses during the term previous to that in which they actually take courses. We timed newspaper releases and advertising to occur during the two weeks previous to this pre-enrollment period.

The publicity campaign involved mailings of course announcements and descriptions to students enrolled in other environmental courses and to student counselors. Course announcements and descriptions were posted on bulletin boards

throughout the campus. Approximately 4,000 of these flyers were mailed and circulated on our campus of 40,000 students. About ten special displays announcing this course were designed by our Instructional Media Center and placed in the University Library, Engineering Building Lobby, and other conspicuous places on campus. Advertis-

The main features of the publicity program which quite likely influenced many students were the apparent comprehensive course organization and the announcement that two nationally recognized speakers, Ralph Nader and a top oil company executive were . . . to present lectures.

ing in the student newspaper and on campus radio was done during the two week period prior to and during the week of pre-enrollment. This publicity campaign was quite successful in that approximately 400 students enrolled for this new course during the pre-enrollment period.

The main features of the publicity program, which quite likely influenced many students, were the apparent comprehensive course organization, and the announcement that two nationally recognized speakers, Ralph Nader and a top oil company executive, were scheduled to present lectures. As can be seen on the course schedule, the course was well organized in a thematic fashion and featured lectures by ChE faculty and off-campus speakers such as Ralph Nader on "The Role of the Public in Solving Problems of the Environment"; C. Howard Hardesty, Jr. Executive Vice-President of CONOCO on "The Role of Industry in Combatting Problems of the Environment"; Raymond Smit of the Michigan House of Representatives on "The Role of Government in Solving Problems of the Environment"; Dean Hadcock, Vice-President of General Foods Company on "Adulteration of Foods," and R. Nelson of Shell Oil Company.

CLASS FORMAT

THE COURSE WAS OFFERED for three credits (MSU is on a quarter system) to the general student body with no prerequisite requirements. The class was scheduled to meet twice per week on Monday and Wednesday evenings from 7:00 to 8:20 P.M. The evening period was selected to minimize possible conflicts with other courses and to make the course available to people in the

TABLE 1
Topics for "Pollution of the Environment"

- Introduction of Faculty; Organization of Course; Grading Procedures
- Introduction to Course—Pollution, Energy, and Economics
- Air Pollutants: Effects on Human Health, Animals, and Plants
- Air Pollution Control, Part I: Source and Control Methods
- Air Pollution Control, Part II: Source and Control Methods
- "The Role of the Public in Combating Problems in the Environment"
- Causes of Water Pollution: Source of Identification of Industrial Pollutants Source and Identification of Domestic and Agricultural Pollutants
- Water Pollution Cures: Control Methods
- Pollution by Oil: Impact and Abatement
- General Question and Answer Session
- Mid-Term Examination
- Solid Waste: Causes and Cures—Methods of Disposal & Recycling
- Noise
- Technology Assessment as Related to Pollution
- Adulteration of Foods
- "The Role of Government in Solving Problems of Environment"
- "The Role of Industry in Solving Problems of Environment
- Advanced Energy Systems: Overall Energy Picture
- Energy: Petroleum and Oil Shale; Coal; Nuclear Energy; Solar Energy & Others
- General Question and Answer Session
- Final Examination

greater Lansing community. Class periods were utilized in most cases with fifty minutes for formal presentation of material, ten minutes for break, and twenty minutes for questions and answers. There were some modifications to this format, especially for the distinguished off-campus lecturers. The question and answer period was handled by asking students to write out questions which were collected during the break and were then answered and discussed during the final twenty minutes of the period.

The class, except for two occasions, met in a large lecture hall which seated approximately 500 students and was equipped with a public address system connected to a tape recording system. All lectures were taped and filed in the library so that students could review lectures or listen to those they may have missed. Most lecturers used well prepared slides or overhead transparencies along with the detailed handouts, containing an outline of the lecture and specific factual material.

Ralph Nader's lecture was held in the main University Auditorium and was open to university community. C. Howard Hardesty's lecture was presented in a large lecture room containing several hundred students and faculty and was broad-

cast via closed circuit television to the university community. Both the Nader and Hardesty lectures were scheduled jointly with the university seminar series entitled "Perspectives In Energy."

Six class sessions were handled by off-campus lecturers, three lectures were presented by MSU non-chemical engineering faculty, and the remaining ten sessions were handled by ChE faculty. All faculty members in the ChE Department participated in the teaching of this course.

Grading was based on multiple choice mid-term and final examinations. Two general informal question and answer sessions were conducted by the ChE faculty just prior to the mid-term and final examinations. MSU Evaluation Services provided assistance at no direct cost to the ChE Department on exam question editing, typing, and administering of examinations, and computer scoring and evaluation. The exams covered material from both lectures and the text book [1] with approximately fifty percent (50%) of the questions from each source.

CLASS COMPOSITION

THERE WERE 365 STUDENTS who actually finished the course and received final grades. The composition of the class was as follows: Arts majors 8%, Natural Science majors 13%, Social

Science majors 18%, Human Medicine majors 2%, Agriculture and Natural Resource majors 17%, Business majors 7%, Engineering majors 19%, Human ecology 3%, Education 3% and those with no preference 10%. It is interesting to note that the largest numbers of students were either freshmen or seniors. This non-homogeneity provided a major in course presentation. This course was taken by most students as a general elective.

STUDENT REACTION AND EVALUATION

STUDENT REACTION and input was sought both at mid- and end-of-term via questionnaires. Over fifty percent (50%) of the students had not taken an environmental course previously. Students were requested to provide written comments at mid-term relevant to improvement of the course. Most comments pertained to improvement of visual aids and to the style of lecturing. As a result, care was taken in subsequent lectures to be certain that visual aids could be read from all parts of the classroom and to have the lecture presentations become more informal. Also, most faculty prepared handouts, containing important information which was projected so that students could spend their time during the lecture fathoming the subject rather than writing notes. These were all definite course improvements.



M. C. Hawley is Professor of Chemical Engineering at Michigan State University and has been on the faculty since 1964. Dr. Hawley's researches are in areas of chemical kinetics and reactor design, chemical separations, and energy. He teaches courses on applied mathematics, chemical kinetics, process design and economics, and serves as a consultant to industry on matters related to process modeling and design and new business ventures. Dr. Hawley received his B.S. and Ph.D. degrees in Chemical Engineering from Michigan State University in 1961 and 1964, respectively. (LEFT)



Esber I. Shaheen is Manager of Education Services at the Institute of Gas Technology (IGT) and is responsible for the preparation of educational materials for IGT's graduate and undergraduate program for the training of LNG Engineers in Algeria. Dr. Shaheen's record as



a Chemical Engineer comprises experience in both industry and education and has authored various articles and books in the environmental field. He received his Ph.D. in Chemical Engineering from the University of Tennessee in 1967. (CENTER)

M. H. Chetrick is Professor and Chairman of the Department of Chemical Engineering at Michigan State University. He was associated with the University of Louisville and the University of North Dakota before coming to Michigan State University in 1963. His industrial experience includes work with Shell Oil Company, Monsanto Company, and Battelle Memorial Institute, as well as consulting for various organizations. He received his B.S. from the University of Alabama and his M.S. and Ph.D. from Ohio State University. (RIGHT)

The Term-End Student Instructional Rating Form indicated was generally quite favorable.

There are three other environmental courses offered at MSU on the subjects of "Resource Ecology and Man," "Environmental Systems," and "The Politics of Ecology." As part of a student research activity, Mr. James Rye reviewed our course relative to the other environmental courses. [2] Mr. Rye attended all of the environmental courses on a regular basis, collected hand-outs, and interacted with faculty and students involved in the courses. The following is an excerpt from Rye's report pertaining to our course:

Chem. Engr. 222 is a very informative class. It is basically awareness oriented, and does not venture into developing problem solving abilities within the student.

ASSESSMENT OF COSTS

BASED ON STUDENT INTEREST, educational benefit to students and faculty, and course enrollment (365 students and 1095 student credit hours) this course appears to have been highly successful. However, it is important to note that there were major costs associated with the development and operation of the course. These costs fall into three categories: (a) Direct Expenditures, (b) On-Campus Manpower, and (c) Off-Campus Contributions of Manpower and Travel. Estimates of these costs are summarized as follows:

	COST (\$)	\$ PER STUDENT QHR
Direct University Expenses	\$ 5,648.17	\$ 5.16
On-Campus Manpower Costs	24,925.00	22.76
Off-Campus Contributions	3,968.16	3.62
Total Cost	\$34,541.33	\$31.54

On-campus manpower costs were determined from estimates of time spent by each faculty member involved on course development, lecture, preparation, class attendance, and course administration. It is anticipated that when this course is offered again this Spring, manpower requirements will be reduced for lecture preparation and class attendance which accounted for approximately forty percent of the on-campus manpower costs during the first offering. Course organization, development, and administration costs would likely continue to be about the same in order to insure a high quality course with attractive features to a large number of students.

The off-campus speakers were a major asset to this course. The expenses and honorariums for Nader and Shaheen were paid with university funds as Direct Expenses. Lecturers Hardesty, Nelson, Hadock, and Smit all contributed their time and effort to this course and travel expenses for each were covered by their respective employers, i.e., Continental Oil Company, Shell Oil Company, General Foods Company, and the State of Michigan. In order to account for this off-campus participation we estimated the value of the off-campus contributions in a highly conservative fashion.

Based on these actual expenses and estimates of manpower and other costs, it can be seen that for this first time offering, the course was relatively expensive. In addition to these itemized costs, during the development and operation of the course all ChE faculty worked "overtime" on such activities as research, proposal writing, paper writing, and personal time to accommodate the large time demands for this pollution course. These would be real costs in the long-term if the course were offered each year.

From the College of Engineering and the Department of Chemical Engineering points-of-view this course generated 1095 student credit hours. From the university standpoint there was simply a new course available with the associated added benefits and costs.

SUMMARY

THE ChE FACULTY at MSU have demonstrated the scope of ChE education can be expanded successfully to include meeting the general education requirements of university students and interested people in the community. If such an effort is to be undertaken at any university, it is important to recognize the costs associated with this expansion in scope. However, it is recognized that such a course provides a very useful and valuable service to society. □

REFERENCES

1. E. I. Shaheen, *Environmental Pollution: Awareness and Control* (Mahomet, Illinois: Engineering Technology Incorporated, 1974).
2. James A. Rye, "Environmental Education at Michigan State University: A Student Reviews His Research With Environmental Courses and The Center for Environmental Quality" (Intra-Michigan State University Communication, Center for Environmental Quality, June 6, 1974).

USE OF A CONTINUOUS SYSTEM SIMULATION LANGUAGE IN CHEMICAL REACTION ENGINEERING

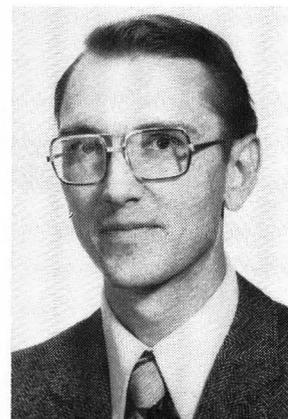
R. D. WILLIAMS and D. WOLF*
University of Arizona
Tucson, Arizona 85721

MANY PROBLEMS IN ENGINEERING, and this is especially true in chemical kinetics and reaction engineering, are dynamic in nature and as such are described by differential equation. In the past, simulation of some of the more interesting of these problems for instructional purposes has been hampered by the lack of easy to use solution techniques. Often the student would become so embroiled in the method of solution that he would not obtain the desired experience with the physics of the problem. For example, setting up nonlinear or high ordered linear problems on an analog computer would involve considerable experience with the particular computer being used. If a digital solution was sought the student might be involved in a nontrivial exercise in numerical analysis. While these experiences are not in themselves bad they do tend to detract from the main point of the problem. The end result has been that often these more difficult problems have been avoided by the professor who feels he has a time constraint to cover some given amount of material.

User oriented Continuous System Simulation Languages (CSSL) have been developed to the point of practical use by undergraduate students in the study of such advanced dynamic systems. Experience with analog simulation and numerical techniques may be covered more specifically in other courses if desired, however, the availability of powerful CSSL will be such that they will be extensively used in industry, justifying their inclusion in the curriculum.

This paper is intended to briefly discuss the

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David Wolf is a graduate of the Technion-Israel Institute of Technology, Haifa, Israel, where he received his BSc, MSc and DSc degrees in Chemical Engineering. In 1963 he spent a year doing postdoctoral work at Carnegie-Mellon University and from 1964 to 1966 he was Assistant Professor of Chemical Engineering at McGill University in Montreal. Since 1966 he has served as Associate Professor and Head of the Isotope Separation Plant at the Weizmann Institute of Science in Rehovot, Israel. He is also presently a Professor of Chemical Engineering at the Ben-Gurion University of the Negev in Beer Sheva, Israel. During the 1972-73 academic year, he spent a sabbatical leave at the University of Arizona. (LEFT)

Dick Williams received his undergraduate degree at Texas Tech University and his doctorate at Princeton University, all in Chemical Engineering. He has been at the University of Arizona since 1968 where his research has been involved primarily with chemical reaction engineering. Current research projects include the development of a hydrogen generator for automotive fuel applications and a study of the hydrometallurgical leach recovery of minerals from their ores with emphasis on characterization of the underlying mechanisms involved. (RIGHT)

philosophy behind such software packages and to illustrate their successful implementation in teaching an undergraduate course in chemical kinetics and reactor engineering in the Department of Chemical Engineering at the University of Arizona. The specific simulation language used in this course is DARE IIIB (Differential Analyzer Replacement, Version IIIB) which was developed for CDC 6000 series computers by the Department of Electrical Engineering at the University of Arizona.

CSSL PHILOSOPHY

A CSSL IS DESIGNED with one purpose in mind, to solve differential equations. It consists of one or several numerical integration algorithms conveniently programmed to allow the user to devote his attention to the problem physics rather than the solution technique. The development of such programs is a result of the logical extension of the concept of analog computer simulation. As digital computation speed and availability have increased they have been increasingly used to simulate the operation of analog computers but with much more accuracy and without the problems involved in scaling of analog computers.

Early digital simulation languages were developed with the analog computer user in mind in order to make his transition an easy one. Analog signal flow diagrams were prepared as usual. Each element of the analog computer program had an equivalent element in the digital program. The "connections" were then made by supplying to the digital computer, in tabular form, the inputs and outputs to the various elements of the model as well as the initial conditions and problem parameters. More modern simulation languages are statement oriented and users need not know anything of analog computers to use them, only a minimal knowledge of FORTRAN and differential equations is required.

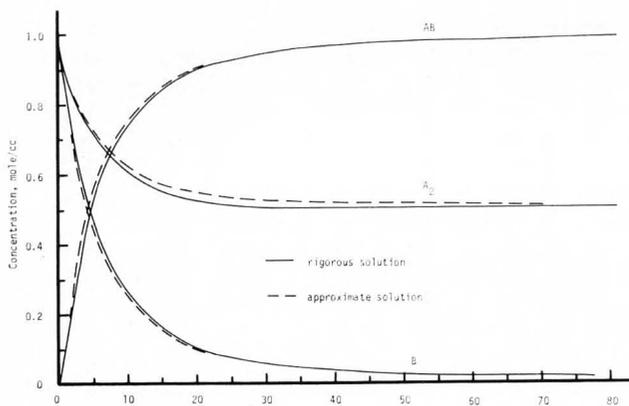


FIGURE 1: Concentration history for Example 1.

The user of DARE IIIB supplies the sequence of differential equations to be solved in FORTRAN form, in any order. In addition, initial conditions and problem parameters are specified as is the integration algorithm to be used (currently from a selection of eight) and the integration parameters (default values are automatically selected if the user does not specify these). Logic

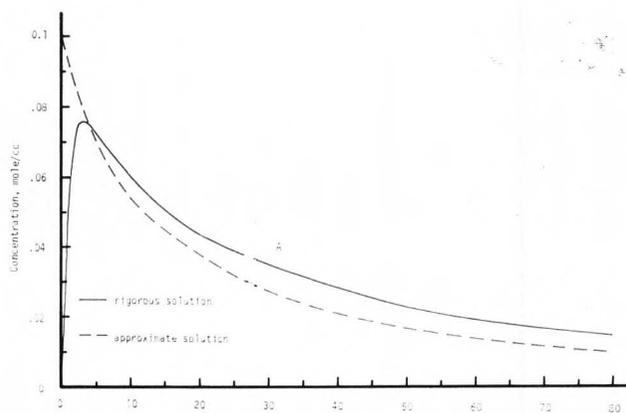


FIGURE 2: Concentration history for reactive intermediate for Example 1.

control may be exercised for iterative boundary valued problems, optimization problems and the like. Output options include lineprinter listings and plots, and Cal-Comp plotter displays. DARE IIIB can handle problems with 100 parameters, 200 state variables, and 350 output variables which is more than sufficient for most problems of interest in the instruction of undergraduates. More specific information on this simulation package is available elsewhere [1, 2, 3].*

CSSL APPLICATIONS

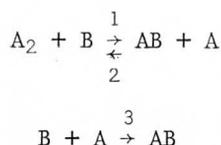
THE APPLICATION EXAMPLES illustrated are taken from a course in chemical kinetics and reactor engineering and though specific to chemical engineering they are typical of the larger class of dynamic problems common to all engineering and scientific disciplines. These applications are (1) the use of the pseudo steady state hypothesis in formulating chemical reaction kinetic rate expressions and (2) the transient analysis of Continuous Stirred Tank Reactors (CSTR). Solution to problems of this type have been reported in the literature, often obtained with great effort. The purpose of this paper is to illustrate the ease with which they may be analyzed in detail by use of a CSSL such as DARE IIIB, making their detailed analysis in an undergraduate course more justifiable.

Example 1—Pseudo steady state hypothesis

When a sequence of chemical reactions occurs which involves a very reactive intermediate, the reaction rate expression may be considerably

*For information on obtaining this simulation package write Dr. J. V. Wait, Dept. of Electrical Engineering, University of Arizona, Tucson, Az. 85721.

simplified by assuming that since the concentration of this reactive intermediate is very small as compared to the stable compounds, its time rate of change in the system will be negligible, except for a brief induction period. This assumption is termed the pseudo steady state hypothesis. Consider for example the following hypothetical chemical reaction sequence.



In this sequence A_2 , B , and AB are stable compounds and A is a reactive intermediate. If these reactions occur isothermally in a closed constant volume reactor, species continuity requires that Equations 1a-1d hold.

$$\frac{d[A_2]}{dt} = -k_1[A_2][B] + k_2[AB][A] \quad (1a)$$

$$\frac{d[B]}{dt} = -k_1[A_2][B] + k_2[AB][A] - k_3[B][A] \quad (1b)$$

$$\frac{d[A]}{dt} = k_1[A_2][B] - k_2[AB][A] - k_3[B][A] \quad (1c)$$

$$\frac{d[AB]}{dt} = k_1[A_2][B] - k_2[AB][A] + k_3[B][A] \quad (1d)$$

In these equations t is time, the k 's are reaction rate constants and brackets symbolize molar concentrations of the species enclosed. Initial conditions are that $[A_2(0)] = [A_2]_0$, $[B(0)] = [B]_0$, $[A(0)] = [AB(0)] = 0$. This set of coupled equations may be simplified by making the pseudo steady state assumption [4] for reactive intermediate, A . This assumption requires that $d[A]/dt \approx 0$ for all time. Equation 1c then reduces to Equation 2.

$$[A] \approx \frac{k_1[A_2][B]}{k_2[AB] + k_3[B]} \quad (2)$$

Replacing Equation 1c with this result then gives a sequence of differential equations containing concentrations only of measurable chemical species, a desirable outcome, and the dimensionality is reduced by one.

Confusion in the use of this approximation arises not from the mathematical mechanics but from the justification for its use, i.e., it is not intuitively obvious to the student that the approximation is a good one or under which conditions it may be. This is where DARE IIIB comes in. Solu-

```

LFN = INPUT
$DI
A2. = -C11*A2*B + C12*AB*AST
AST = C11*A2*B/(C12*AB + C21*B)
B. = -C11*A2*B + C12*AB*AST - C21*AST*B
AB. = C11*A2*B - C12*AB*AST + C21*AST*B
TOTA = 2.*A2 + AST + AB
TOTB = B + AB
A2I. = -C11*A2I*B1 + C12*AB1*ASTI
ASTI. = C11*A2I*B1 - C12*AB1*ASTI - C21*ASTI*B1
B1. = -C11*A2I*B1 + C12*AB1*ASTI - C21*ASTI*B1
AB1. = C11*A2I*B1 - C12*AB1*ASTI + C21*ASTI*B1
TOTAL = 2.*A2I + ASTI + AB1
TOTB1 = B1 + AB1
7/8/9
7/8/9
$SYSTEM TMAX = 100.0,NPOINT = 51$
$STI A2 = 1.0,B = 1.0, AB=0.0, A2I=1.0,B1=1.0,ASTI=0.0,
AB1=0.0$
$UND C11 = 0.1,C12 = .05,C21=1.0$
7/8/9
LIST,A2,B,AST,AB,TOTA,TOTB
LIST,A2I,B1,ASTI,AB1, TOTAL,TOTB1
PLOT, A2,A2I,B,B1,AB,AB1
PLOT,AST,ASTI
7/8/9
7/8/9
7/8/9
6/7/8/9

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FIGURE 3: Program used in solving Example 1.

tions to Equations 1 for various values of the reaction rate constants may be easily obtained and compared to solutions of the equations when the approximation is made. In doing this, values of rate constants or rate constant ratios may be obtained for which the approximation is appropriate. Table 1 gives the lineprinter concentration history for the rigorous case when $[A_2(0)] = [B(0)] = 1$ and $k_1 = 0.1$, $k_2 = 0.05$, and $k_3 = 1.0$. Lineprinter plots of the state variables are given in Figures 1 and 2. In Figure 1 concentrations of stable compounds are plotted against time for the rigorous case (solid lines) and with the steady state approximation (dashed line). It may be seen that the approximate concentration histories for these compounds are in good agreement with the exact values. Figure 2 gives the same comparison for unstable intermediate, A . The discrepancy in this case results from the non-zero initial value of $[A(0)]$ as given by Equation 2 when the approximation is used.

This exercise provides a better understanding of the implications of making the pseudo steady state assumption, but without the agony of a complicated analysis. Figure 3 gives the entire program supplied in obtaining these results.

Example 2—Unsteady state CSTR and steady state multiplicity

An important area of chemical reactor engineering is the transient response of continuous stirred tank reactors, especially when multiple steady states are possible for a given set of operating conditions. The possibility of multiple steady states and stability is a new concept to students in the reactor engineering course, but lend themselves readily to student investigation using a CSSL. The differential equations to be solved in this case, with the usual assumptions [5], are:

$$q\rho C_p(T_F - T) + US(T_c - T) + \frac{r_i(-\Delta H_R)V}{a_i} = V\rho C_p \frac{dT}{dt} \quad (3a)$$

$$q(C_{iF} - C_i) + r_i V = V \frac{dC_i}{dt} \quad (3b)$$

The kinetic rate expression, r_i , is left implicit in these equations and is specified in a separate algebraic statement for ease in adapting the program to investigate the effect of various types of kinetics. For simplicity a first order irreversible

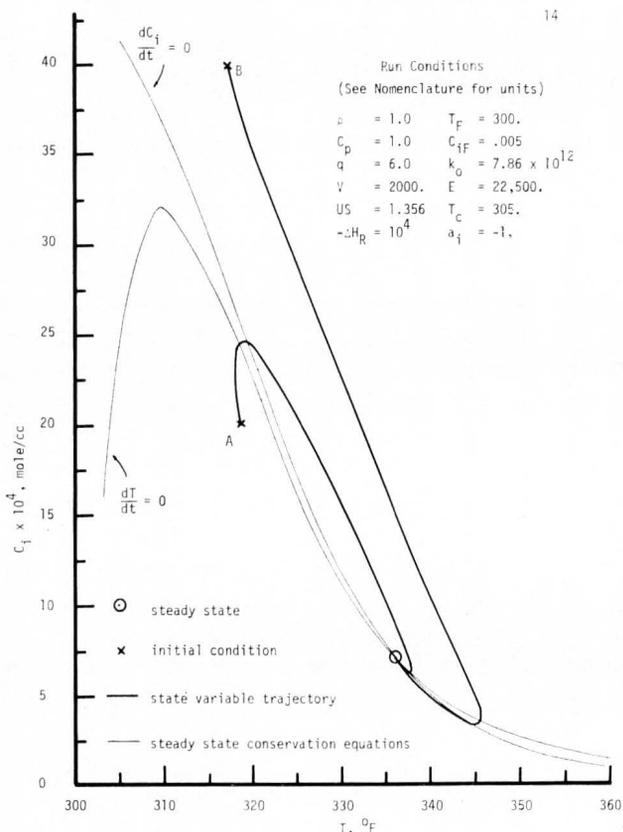


FIGURE 4: Phase plane plot for CSTR with a single steady state.

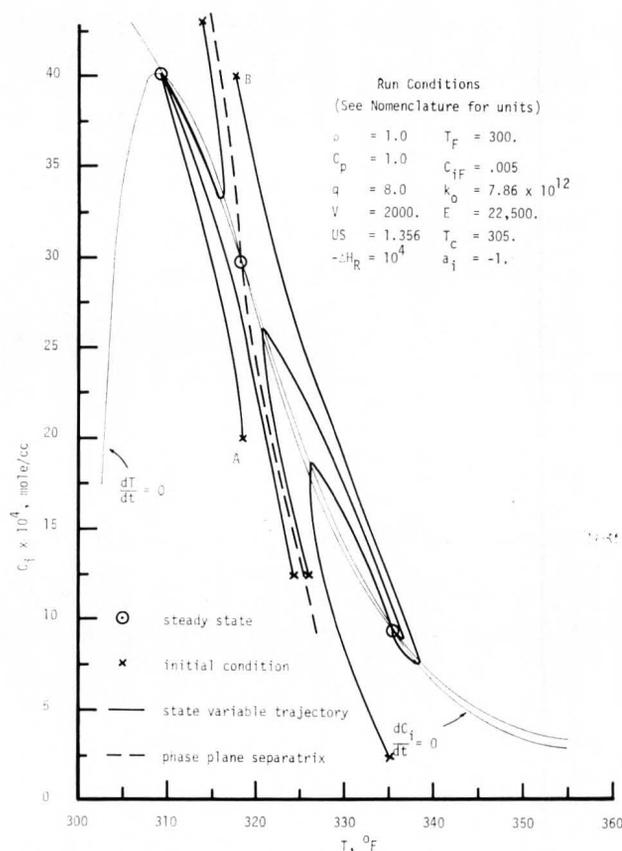


FIGURE 5: Phase plane plot for CSTR with multiple steady states.

rate expression may be used with Arrhenius temperature dependence.

$$r_i = -k C_i \quad (4a)$$

$$k = k_0 \exp(-E/RT) \quad (4b)$$

The differential equations may now be solved subject to an appropriate set of initial conditions, $C_i(0)$ and $T(0)$.

Reactor conditions (adapted from Bilous and Amundson [6]) which will give single and multiple steady states are given in Figures 6 and 7. Steady state values of reactant concentration and temperature in the reactor are found by setting their derivatives equal to zero in Equations 3 and solving the two resulting algebraic equations. A lineprinter plot of these equations for conditions resulting in multiple steady states is given in Figure 4. The three intersection points correspond to the possible steady states for the conditions imposed.

A typical lineprinter phase plane trajectory is given in Figure 5. The existence of multiple steady states is readily confirmed for the second set of reactor conditions. Reactor sensitivity to variables

other than flow rate may also be easily investigated.

CONCLUSION

OBVIOUSLY MANY OTHER applications of CSSL may be envisioned, not only in kinetics and reactor engineering, but in other areas of chemical engineering and other engineering and scientific disciplines as well. These languages should be used as instructional aids in the investigation of advanced dynamic systems on the undergraduate level. They allow considerable ease of analysis such that the student may devote his attention to a detailed study of system mechanics. This does not constitute much of a compromise in

LFN = INPUT

\$D1

$$C1 = Q/V$$

$$C2 = -DHRXN/(RO*AA*CP)$$

$$C3 = US/(V*RO*CP)$$

$$RA = -RKO*EXP(-E/(R*TEMP))*CA$$

$$CA. = C1*(CAO-CA) + RA$$

$$CB = CAO-CA$$

$$TEMP. = C1*(TF-TEMP) + C2*RA + C3*(TC-TEMP)$$

7/8/9

7/8/9

$$\$SYSTEM TMAX = 5000., DT = 0.01, DIMIN=0.01, NPOINT = 51\$$$

$$\$ST1 CA = 0.002, TEMP = 318.5\$$$

$$\$UND RO=1., CP=1., Q=8.0, V=2000., US = 1.356, DHRXN = -10000., TF = 300., CAO = 0.005, RKO=7.86E+12, R=1.9872, TC=305., AA=-1.5, E=22500.5$$

7/8/9

LIST, CA, CB, TEMP

PLOTXY, TEMP, CA

PLOT, CA, CB

PLOT, TEMP

7/8/9

6/7/8/9

FIGURE 6: Program used in solving Example 2.

the education process since the details of numerical analysis are normally covered in other, more basic, applied math courses. Digital simulation is fast replacing analog simulation and the modern CSSL represents an extremely high level, user oriented simulation package. □

REFERENCES

1. Trevor, A. B., "DARE IIIB, A Digital Simulation System", MS Thesis, University of Arizona, Tucson, 1971.
2. Trevor, A. B. and Wait, J. V., DARE IIIB User's Manual, CSRL MEMO 221, University of Arizona, Department of Electrical Engineering, Tucson, July 1971.
3. Trevor, A. B., and Wait, J. V., "DARE IIIB—A CSSL-type batch-mode simulation language for CDC 6000-Series Computers", *Simulation*, June 1972, p. 215.

4. Benson, S. W., *The Foundations of Chemical Kinetics*, McGraw-Hill Book Co., New York, 1960, pp. 50-54.
5. Smith, J. M., *Chemical Engineering Kinetics*, McGraw-Hill Book Co., New York, 1970, p. 184 and 236.
6. Bilous, D. and Amundson, N. R., "Chemical Reactor Stability and Sensitivity", *A.I.Ch.E. Jour.*, 1, December 1955, p. 513.

NOMENCLATURE

a_i	Stoichiometric coefficient, dimensionless.
C_1, C_{1F}	Reactant concentration in reactor and reactor feed respectively, moles/cc.
C_p	Reacting fluid heat capacity, cal./ (gm.) (°C.).
E	Activation energy, cal./mole.
ΔH_R	Energy of reaction, cal./mole.
k, k_0	First order reaction rate constant and pre-exponential factor respectively, sec ⁻¹ .
k_1, k_2, k_3	Second order reaction rate constants, liter/ (mole) (sec.).
q	Volumetric flow rate, cc./sec.
r_i	Reaction rate, mole/ (cc.) (sec.).
R	Gas law constant, cal./ (mole) (°K).
S	Heat exchange surface area, cm. ² .
t	Time, sec.
T, T_F, T_c	Temperature in reactor, reactor feed, and to heat exchange coil respectively, °C.
U	Overall heat transfer coefficient, cal./ (cm. ²) (°C.) (sec.).
V	Reactor volume, cc.
ρ	Reacting fluid density, gm./cc.
$[]$	Denote molar concentration of enclosed species.

THERMOMOMETRY: Levenspiel

Continued from page 105.

factor from our lives (all thermo students would cheer this), that miserable gas constant. Thus, for a mole of ideal gas

$$pV = RT \text{ would become } pV = T$$

$$C_p - C_v = R \text{ would become } C_p - C_v = 1,$$

for one mole of any substance

$$C_p \text{ and } S \text{ would be dimensionless}$$

and the gas constant R , the Boltzman constant k , and Avogadro's number A would be related as follows:

$$R = \frac{k}{A} = 1 \text{ or } k = \frac{1}{A}$$

Imagine, the letter R would be free forever more to play new roles. In fact so would the Boltzman constant k . With all the new concepts of science crying for symbols what a boon this would be.

I wonder whether a change to so pure and rational a temperature scale could receive serious consideration today, or is science too big, with too much inertia? We'll see. □

DEMONSTRATING CATALYTIC REACTOR STABILITY

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THE PURPOSE OF THIS communication is to bring to the attention of the chemical engineering community an example of a catalytic reaction that among other things, can be used to demonstrate reactor stability. The demonstration uses very simple and inexpensive equipment, is easy to assemble (taking less than an hour), and is highly portable.

The reaction itself is the catalytic oxidation of ammonia. As an example of catalysis, this reaction is well known in various forms in the literature on chemical demonstrations [1, 2]. However, the published accounts of it fail to appreciate not only that the reaction is controlled by film heat transfer, but also that the experiment can be used for a demonstration of catalytic reactor stability.

The apparatus used in the demonstration consists of:

- 1 200 ml erlenmeyer flask
- 1 pair of tongs
- 3 5-cm lengths of glass rod (3 mm diameter)
- 1 bottle of concentrated ammonium hydroxide solution
- 1 propane torch or bunsen burner
- Several 30-cm lengths of copper wire of varying diameters (AWG Nos. 12, 18, 24; see Diameters in Table 1).

We shall first illustrate the phenomenon of control of reaction by heat transfer across the gas film. First, add about a 1-cm depth of ammonium hydroxide solution to the bottom of the flask. Then, using the No. 18 copper wire, fashion a helix of about 3 or 4 turns $1\frac{1}{2}$ cm in diameter at one end of the wire, and wind a turn or two around a glass rod such that the helix can hang inside the flask within $\frac{1}{2}$ cm of the surface of the ammonia solution. A schematic diagram of this configuration is shown in Figure 1. Grasping the wire and glass rod with the tongs, heat the copper helix in the torch flame to incandescence (yellow-orange). Then quickly place the wire in the flask.

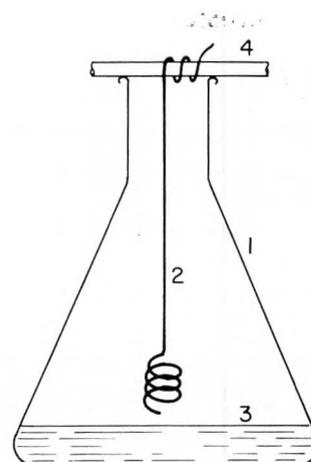


FIGURE 1. Diagram of the Apparatus.

Legend: 1 — erlenmeyer flask (200 ml), 2 — copper wire, 3 — concentrated ammonium hydroxide solution, 4 — glass rod.

The wire will continue to glow for some time (perhaps 10 to 15 min. or until the ammonia coming off the solution becomes too weak to support a reasonable rate of oxidation).

The experiment may be repeated using the No. 24 copper wire. The wire will reach yellow heat and melt. With No. 12 wire, however, the temperature will slowly decline during which the yellow-orange glow turns dull red and is finally extinguished. These various observations demonstrate the control of a catalytic reaction by heat transfer across the gas film.

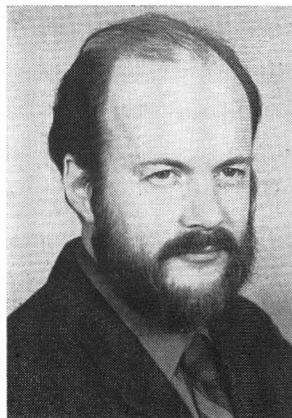
Using the No. 18 copper wire, we can now illustrate the phenomenon of reactor stability. With the helix glowing in the flask, withdraw it fairly abruptly above the mouth of the flask. The glow should start to fade to a bright red. Immediately replace the wire in the flask. The glow should slowly return to the original yellow-orange colour. If the coil is once again withdrawn, but this time allowed to fade to dark red, and replaced in the flask again, the glow will not return. Rather, the glow will continue to be extinguished. This illustrates the phenomenon of reactor stability. Similar observations can be made with the No. 24 wire, except that the response time is much smaller. Also, some practice may be required to avoid melting the wire. With the No. 12 wire, a demonstration of stability is not possible, since the glow gradually declines after insertion in the flask. Perturbing the temperature by removing the wire from the flask simply hastens the decline. Typical stability results are offered in Table 1.

Some variation in these observations will occur depending upon the precise geometry of the copper coils, the proximity to the ammonia solution, and the concentration of the solution. The observations in Table 1 refer to fresh solution.

By now, an observer will have noticed a number of local changes in temperature on the surface of the copper coils. These take the form of the occasional flickering of the colour of the surface, sometimes in response to movement of the coil, at other times apparently in response to convection within the flask. Without pursuing the exact cause of these fluctuations, one may observe that the temperature colour changes are fairly large, and that they occur swiftly across the surface of the catalyst wire, despite its thermal inertia. This observation illustrates that transient temperatures are easily produced in catalyst particles with exothermic reactions.

Finally, questions that should be asked of students watching this demonstration include:

- What observations make it clear that the (pseudo) steady state reaction is heat transfer rather than mass transfer controlled?
- Estimate from the colour of the wire (or its melting point) a temperature difference across the gas film.
- Why does the thinner No. 24 wire become hotter than the thicker No. 18 wire? In your answer include the effects of radiation as well as conduction along the wire.
- Is conduction responsible for the gradual loss of



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TABLE 1
Typical Stability Observations

Wire gauge No. (AWG)	Diameter		Observations
	(in.)	(cm.)	
12	0.081	0.21	Bright glow on entering flask gradually fades to extinction. Stability demonstration not possible.
18	0.040	0.10	Glow readily stabilizes at bright yellow-orange; when small temperature perturbation is introduced, glow slowly recovers to original colour; large perturbation of temperature extinguishes glow.
24	0.020	0.051	Glow can increase to yellow heat, melting wire. Observations similar to No. 18 wire, but with more rapid responses.

glow in No. 12 wire? An experimental answer may be easiest here by cutting the helix off the No. 12 wire sample, and holding it by a thin wire (say No. 22 copper), heating to incandescence, and placing it in the flask.

- Explain by means of a diagram the return of the wire to its former temperature after withdrawal from and replacement in the flask. □

REFERENCES

1. G. Fowles, *Lecture Experiments in Chemistry*, 6th Ed., p. 178, G. Bell and Sons Ltd., London 1963.
2. N. Nechamkin and J. J. McClarnon, p. 169, 1960 Reprint Edition of "Tested Demonstrations", *J. Chem. Educ.*, H. N. Alyea, (editor).

ChE book reviews

Introduction to Control Systems

By D. K. Anand

Pergamon Press, Inc. 1974

Reviewed by Doug Wilde, Stanford University

This text is interchangeable with many other books on elementary linear control theory, all of which are good for electrical and mechanical engineers, and none of which deal with chemical engineering systems. There are books much more suitable for courses taught exclusively to chemical engineering students. Still other books would be better for a general control course mixing chemical with mechanical and electrical engineering students. This book would be appropriate only for a general control course not catering to chemical engineering students at all, and it is little different from earlier texts written for the same purpose. □

SELF-TAUGHT THERMO: Tiller

Continued from page 117.

exact or inexact? A logical approach would revolve around the fact that both $d'W$ and $d'Q$ are inexact. Work with two inexact differentials like the following:

$$\begin{aligned}d'u &= ydx + dy \\d'v &= dx + x^2dy\end{aligned}$$

Subtract one from the other to obtain some idea of the possibility of the difference leading to an exact or inexact differential.

2) Test Equation (9) for exactness (if you can) by using the relation $\partial p/\partial y = \partial Q/\partial x$ for an exact differential of the form $dz = pdx + Qdy$.

Work on these two questions before looking at the answers that follow.

ANSWERS

1) It is demonstrated that no linear combination of certain inexact differentials can be made exact and the following comment added:

It would be judicious (but not necessarily correct) to think that dz in Equation (9) was inexact.

2) Equation (9) is restricted to a reversible, quasiequilibrium process. Therefore, any conclusions drawn from Equation (9) will apply only to those restrictions.

Writing the equation in the form

$$dx = d'Q - pdV \quad (10)$$

We might say the coefficients could be derived from

$$dz = Md'Q + NdV \quad (11)$$

and apply the rule

$$\left(\frac{\partial M}{\partial V}\right)_Q = \left(\frac{\partial N}{\partial Q}\right)_V \quad (12)$$

Such a mathematical process would imply that Q is a state variable, i.e., $Q=f(p,V)$. However, Q is a path function; and the operations used with properties like p,v,T cannot be used with Q and Q . For example, writing

$$dz = d'Q - d'W \quad (13)$$

it could be argued dz is exact because

$$\frac{\partial}{\partial w} (1) = 0 \text{ and } \frac{\partial}{\partial Q} (-1) = 0 \quad (14)$$

Thus Equation (14) does not have the same status as

$$dz = dx - dy \quad (15)$$

where it is obvious $z = x - y$.

We conclude it is impossible to apply the $\partial p/\partial y = \partial Q/\partial x$ test.

INTERNAL-ENERGY

THERE IS NO PURELY mathematical method to demonstrate the exactness or inexactness of dz . It is necessary to resort to experiment, because the first law rests upon the basis of factual evidence. Place Equation (9) in integrated form

$$\int_c dz = \int_c d'Q - \int_c d'W \quad (16)$$

in which the circuit integral starts and stops at the same point. From the "half" law of thermo-

dynamics*, we assume there are two independent variables, say p, T , or p, V over which the circuit integral must be performed. In working with $d'Q$, there will be portions of the cycle when Q and W are positive or negative. Let us call the sum of all the heat transferred to the system Q_1 and all transferred from the system Q_2 where both quantities are considered as positive numbers. Then

$$\int_c d'Q = Q_1 - Q_2 = Q_{\text{net}} \quad (17)$$

where Q_{net} represents the net heat transferred to the system. With a similar situation for W , Equation (16) becomes

$$\int_c dz = Q_{\text{net}} - W_{\text{net}} \quad (18)$$

Overwhelming experimental evidence points to-

ward $Q_{\text{net}} = W_{\text{net}}$ and $\int_c dz = 0$. This is the essential point of *The Law of Conservation of Energy: The Heart of the Subject*.

The quantity z now possesses special interest as it is a property of the system. It deserves a name. Thermodynamicists generally call it internal energy. It represents the storage of heat or work as they are transferred to the system. It is frequently given the symbol U, I , or E . In accord with the textbook, we shall choose U and rewrite Equation (18) in the form

$$dU = d'Q - d'W \quad (19)$$

The integrated form is

$$\Delta U = U_2 - U_1 = Q - W \quad (20)$$

For a frictionless, quasiequilibrium process in which there is only work of expansion

$$dU = d'Q - dpV \quad (21)$$

Various examples involving the First Law follow.

ENTROPY

IN THERMODYNAMICS, it is frequently useful to define certain quantities which appeal to the senses like pressure and temperature or may be conceptualized as voltage, current, and resistance. In this exercise, a powerful but abstract

*In a previous lecture, students were introduced to the zeroth law and the "half law". The latter which lies between the zeroth and first laws states that Boyle (or Mariotte) and Charles showed that $\int_c dv=0$ when p and T were changed and, therefore, that $v=f(p,T)$.

concept which arises out of application of an integrating factor to $d'Q$ will be developed.

Our task is to seek a generalized displacement which yields heat transferred in a reversible process. Concepts necessary to this "lecture" are:

- First Law of Thermodynamics
- Integrating factors which turn inexact into exact differentials

GENERALIZED DISPLACEMENT FOR HEAT TRANSFERRED

In general, work is given by

$$d'W = \pm XdY \quad (1)$$

where X is a generalized force and Y is a generalized displacement.

X and Y are both properties, and they possess exact differentials. W, is not a property, and its differential is inexact. We know from the study of differentials an inexact differential multiplied by an integrating factor yields an exact differential. From Equation 1 we can see $(1/X)$ serves as an integrating factor for $d'W$ because dY is exact. Various kinds of generalized quantities are shown in Table 1 along with a description of the type of work involved.

TABLE 1

PROCESS	GENERALIZED FORCE	GENERALIZED DIS-PLACEMENT	EQUATION
Fluid expansion	Pressure P	volume V	PdV
Elastic solid	Force F	length L	FdL
Electric	Voltage E	charge Q	$-EdQ$
Surface charge	Surface tension s	area A	$-sdA$
Heat transfer	Temperature T	unknown Y*	$\pm TdY$
Mass transfer	unknown X*	mass m	$\pm Xdm$
Potential energy	weight ($-mg$)	distance z	$-mg dz$

In Table 1, it is apparent there are two missing quantities marked by * which have not been previously encountered in non-thermodynamics courses. If we accept Equation (1) as valid for expressing work done in general terms, there must be a generalized displacement Y for transfer of heat. We assume temperature is the generalized force which causes heat to flow. That is not the only assumption which could be made. From elementary kinetic theory, we know that temperature is proportional to the kinetic energy of the molecules. We might assume the generalized force was the square of the velocity or the velocity of the molecules. Such assumptions would lead to a somewhat

different if equivalent conclusion. To simplify the problem, we shall assume T is *the* generalized force for heat transfer.

When a crystal dissolves in a liquid, there is necessarily a transfer of energy. In fact, any time there is a transfer of mass from one phase to another, there will be an energy transfer. Thus if a differential mass, dm , passed from one phase to a second, there would be an energy transfer of the type Xdm .

Previous knowledge from non-thermodynamic sources does not provide us with definitions of the generalized quantities needed for heat and mass transfer. We shall seek an answer for heat transfer at this time but will postpone seeking a solution for mass transfer until we study multicomponent systems and define new thermodynamic functions such as Gibbs free energy and the work function.

There is no general formula for finding new thermodynamic functions. There is some controversy among thermodynamicists about rigorous methods for defining our Y in the equation

$$d'Q = \pm TdY \quad (2)$$

The method which will be followed is not rigorous. It will apply only to a specialized case of an ideal gas in a frictionless, quasiequilibrium, non-flow process. Thus the method applies to a highly-restricted, non-existent situation. Nevertheless, the method will produce the same answer which can be obtained from more rigorous (and controversial) methods.

We shall give the name of entropy to our generalized displacement Y before we find it. Our method will involve integrating factors. The process we are about to consider was commented on by Clausius in an appendix of his book on the mechanical theory of heat. He recognized the lack of rigor at that time (close to 1850).

Concepts that are needed to understand this development include (1) integrating factors and (2) internal energy of an ideal gas.

QUESTIONS

Take the function

$$z = xy + x^2 \quad (3)$$

and find its differential. Then divide the differential by x to obtain a new differential du . Show du is inexact by

*The generalized forces are generally, but not always, intensive quantities. Pressure, surface tension, and electric potential are examples of intensive variables. The generalized displacements are extensive variables in that they are dependent on length, area, volume, mass, or charge. Gravitational force mg is an example of a force which is extensive rather than intensive.

means of the $\partial P/\partial y = \partial Q/\partial x$ test. Then assume there is an integrating factor $\lambda(x)$ which is a function of x alone and find λ . Attempt to find another integrating factor which is a function of y alone.

Answer

The differential

$$du = (z + y/x)dx + dy \quad (4)$$

is shown to be exact. Assuming λ is an integrating factor, it is demonstrated that $\lambda(x) = x$ and that no integrating factor which is a function of y exists.

INTERNAL ENERGY AND ENTROPY

AN IDEAL GAS CONSISTS of point masses having no gravitational, electrical, or magnetic interaction. Therefore an ideal gas can only have translational kinetic energy. From kinetic theory, it can be shown that

$$PV = \frac{2}{3} N \left(\frac{1}{2} Mu^2 \right) \quad (5)$$

where u is the square root of the average velocity of the molecules. Thus the molar kinetic energy is directly related to the ideal gas temperature. In fact

$$RT = (2/3) (\text{molar K.E.}) \quad (6)$$

In deriving (5) all but translational kinetic energy has been neglected. The molecules are assumed to be incapable of having rotational, vibrational, gravitational, magnetic or electrical energy. Therefore, the internal energy of an ideal gas depends only on its temperature. We can write

$$\left(\frac{\partial u}{\partial v} \right)_T = 0; \left(\frac{\partial u}{\partial p} \right)_T = 0 \quad (7)$$

which states that

$$u = u(T) \quad (8)$$

The first law for a non-flow, frictionless, quasi-equilibrium process can be written as

$$d'Q = dU + pdV \quad (9)$$

The generalized specific heat is defined by

$$d'Q = NCdT \quad (10)$$

where C is the molar specific heat. For a constant volume process, combining (9) and (10) yields

$$d'Q = NC_v dT = dU \quad (11)$$

Integration gives

$$Q = \Delta U = NC_v \Delta T = NC_v T + U_0 \quad (12)$$

At this point, a number of examples involving specific heats and ideal gases are presented.

SEARCHING FOR ENTROPY

WE ARE LOOKING for the generalized displacement in the equation

$$d'Q = \pm TdY \quad (13)$$

Basically we want to find a function which is an integrating factor of $d'Q$. We do not know if T itself will turn out to be the function we are looking for. However, we shall experiment and see what results.

You are to do the following:

- Write the first law for a general non-flow process and solve for $d'Q$.
- Assume that work is restricted to a frictionless, quasi-equilibrium expansion process.
- Assume the gas is ideal and replace dU by $NC_v dT$.
- Eliminate P by means of $PV = NRT$.
- Place the differential of Q in the form

$$d'Q = AdT + Bdv \quad (14)$$

- Find an integrating factor which is a function of T .

Do this work before continuing. The answer is on the next sheet.

NOTE: Basically the student develops the concept of entropy in this example by himself. By providing him the appropriate catalyst, a situation is produced in which entropy naturally falls out of the process of finding an integrating factor for $d'Q$. To the equation

$$d'Q = NC_v dT + PdV = NC_v dT + \frac{NRT}{v} dv \quad (15)$$

an integrating factor $\lambda(T)$ is applied. Then applying the rule for exactness

$$\frac{\partial}{\partial v} (\lambda NC_v)_T = 0 = \frac{\partial}{\partial T} \left(\frac{\lambda NRT}{v} \right)_v \quad (16)$$

The product λT must be constant, and $\lambda = 1/T$. Therefore,

$$\frac{d'Q}{T} = dY = NC_v \frac{dT}{T} + NR \frac{dv}{v} \quad (17)$$

It can be seen that dY is exact. We shall call it entropy and use the letter S .

SIGNIFICANCE OF ENTROPY

IT HAS BEEN SHOWN that $1/T$ is an integrating factor for $d'Q$. Therefore, the quantity $dS = d'Q/T$ must be an exact differential. It fulfills our search for a dY to satisfy the relation $d'Q = \pm XdY$. The question of sign has been settled; a plus is used. Further as Q is proportional to mass (lbs. or lb-moles), it can be written as $Q = Nq$. Then

$$dS = \frac{d'Q}{T} = \frac{Nd'q}{T} = Nds \quad (18)$$

and we see entropy is an extensive variable which is proportional to mass. (In the accompanying figure (Three graphs show x (generalized force) vs Y (generalized displacement), P vs V , T vs S) we see that the heat transferred is given by the area under the T - S curve in accord with

$$Q = \int T dS \quad (19)$$

There is a direct correlation between the area

under the X-Y, P-V, and T-S curves. Each area corresponds to some kind of work.

There are an infinite number of integrating factors for $d'Q$. Each one would lead to an exact differential with a new X and Y. As an example, v^{k-1} where $k = c_p/c_v$ is an integrating factor for the case of an ideal gas. Thus

$$v^{k-1} d'Q = dY \quad (20)$$

or

$$d'Q = v^{1-k} dY \quad (21)$$

There is no special value attached to this XY combination. Further, $1/T$ has general application to all processes, although the present development has been restricted to ideal gases. There may be some useful integrating factors other than $1/T$, but we shall not search for them.

WHAT DO WE HAVE?

WE HAVE FOUND a function, entropy, which is a property of the system. We shall be able to show that entropy plays a very useful role in thermodynamics. But that comes later. We now ask, what do we have? Usually when a physical quantity is defined, there is some material concept involved which appeals to our senses. In the case of the other generalized displacements in Table 1, it is simple to visualize distance, area, and volume. The concept of electric charge is not difficult to imagine. In the case of magnetic quantities, we have to use a little more imagination. The generalized forces can be understood in terms of measuring instruments. Everyone thinks of a mercury column in glass as signifying tempera-

ture. A dial on a voltmeter gives a direct reading of voltage.

If we went deeply into measurement in a sophisticated manner, we would find the simple concepts must be examined with much more care. We would discover temperature is difficult to define precisely. In the end, we would be asking how can we measure the variables and how can we assure reproducibility and comparative accuracy.

Entropy suffers in comparison with other physical quantities, because we have no *entropometer* from which we can read values of entropy. However, if we can show how to measure entropy, that should enable us to form an intellectual if not a physical notion of what it is.

Returning to the equation for an ideal gas, we have on a unit mass basis

$$ds = d'q/T = C_v \frac{dT}{T} + R \frac{dv}{v} \quad (22)$$

This equation can be integrated to give

$$s = C_v \ln T + R \ln v + s_0 \quad (23)$$

or

$$\Delta s = C_v \ln T/T_0 + R \ln v/v_0 \quad (24)$$

These equations tell us how to measure s or Δs for an ideal gas. However, we must make measurements of T and v and then *calculate* s . We could develop an instrument which would translate (24) into something which could be visibly seen. Such an instrument would not be very useful.

We must be satisfied with a mathematical and intellectual rather than a familiar physical concept of entropy. \square

ChE book reviews

INTRODUCTION TO PROCESS ECONOMICS

F. A. Holland, F. A. Watson and J. K. Wilkinson, John Wiley & Sons, 290 pages.

Reviewed by James H. Black, University of Alabama, University, Alabama

This book is intended as an undergraduate text for the process engineering disciplines, such as chemical, metallurgical, and mineral engineering. It would also give an excellent introduction to process economics for the practicing engineer or serve him as an excellent reference book. It is, as the title states, a book covering process economics; but some wider aspects, such as some of the management sciences, are also presented.

The organization of the book is excellent. It is divided, logically, into two parts: the elements of profitability assessment and the elements of decision making. Thus, the reader first gets a complete treatment of time value of money calculations, followed by chapters on profitability estimates, uncertainties in profitability estimates, capital cost estimates, and manufacturing cost estimates. The second part of the book covers such decision making tools and techniques as statistical analysis, curve fitting and trend analysis, linear programming, financial and cost accounting, price and cost trends, value engineering, marketing, and some material on risk and insurance.

This is a good book, well worth the cost. It would be of particular interest and value to those who found use in the recent series of articles on engineering economics, by the same authors, in *Chemical Engineering* magazine.

GEORGIA TECH'S PULP AND PAPER ENGINEERING PROGRAM

GEORGE R. LIGHTSEY
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A program of technical electives in pulp and paper engineering was established in the fall of 1974 at Georgia Tech to help meet the need of the pulp and paper industry for engineers both well grounded in engineering fundamentals and also knowledgeable of the special problems of the pulp and paper industry.

The pulp and paper engineering (PPE) program, while centered in the Chemical Engineering School, is multidisciplinary in nature. Five technical electives in PPE have been approved for addition to the curriculum. Three of these are offered in the Chemical Engineering School and deal with the basic processes required for conversion of wood to pulp. The other two courses, a survey course and a course dealing with paper preparation and properties, is team taught by personnel from Ch.E. and Textile Engineering and is co-listed in both schools.

A committee composed of faculty from the Schools of Chemical, Textile, Mechanical, and Ceramic Engineering and the School of Architecture directs the program. An Industry Advisory Committee made up of pulp and paper industry leaders has been formed to help guide the development of the PPE Program.

Georgia Tech does not plan to develop a pulp and paper engineering degree program. The goal of the PPE Program is an engineer completely competent in the basic engineering fundamentals and who also possesses special training in pulp and paper engineering.

PULP AND PAPER MANUFACTURING is one of the major industries in the U.S. with manpower needs of up to 3000 new B.S. technical graduates each year. A large number of these B.S. graduates are employed in Georgia which is the

leading state in the production of paper products with 20 pulp and paper manufacturing plants.

A survey in 1970 by the Technical Association of the Pulp and Paper Industry (TAPPI) found that about 80% of the new B.S. graduates hired by the pulp and paper industry had no special training in pulp and paper engineering. Consequently, most pulp and paper manufacturers must devote the first 3 to 12 months of a new engineer's employment to on-the-job training in the basics of pulp and paper engineering. This often results in low productivity for an extended period of time for the company and a feeling of futility by the new engineer.

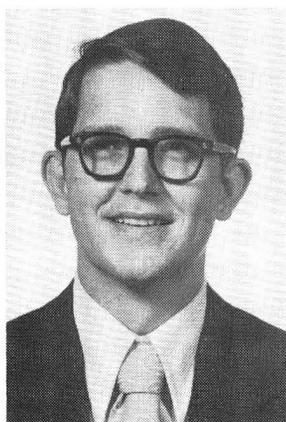
An interesting result revealed by the TAPPI survey was that many pulp and paper companies felt that graduates from pulp and paper degree programs who were trained in pulp and paper technology were lacking in engineering fundamentals. The pulp and paper industry, the survey showed, wanted engineers (usually Ch.E.) both well grounded in engineering fundamentals and also knowledgeable of the special problems of the

The pulp and paper engineering program is centered in the Ch.E. school and offers five technical electives for addition to the curriculum.

pulp and paper industry. A program of technical electives in pulp and paper engineering was established in the fall of 1973 at Georgia Tech to help meet this industry need.

COURSES TAUGHT

THE PULP AND PAPER engineering (PPE) program, while centered in the Ch.E. school, is



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multidisciplinary in nature so that students from any engineering discipline may participate. A committee is composed of faculty from the schools of Chemical, Textile, Mechanical, and Ceramic Engineering and the School of Architecture directs the program. Five technical electives in PPE have been approved for addition to the curriculum (Table I). The first of these, "Survey of Pulp and Paper Technology", is a course dealing with all aspects of pulp and paper manufacturing. It is team taught by personnel from Chemical and Textile Engineering and is co-listed in both schools. This course is designed for students who may not have a strong interest in pulp and paper, but want a general understanding of the industry. The first half of the course is taught by chemical engineering faculty and includes an introduction to the chemical and physical properties of wood. The major pulping and bleaching processes are also described. The second half of the course is taught by textile engineering faculty. The fundamentals of paper making are covered with emphasis on the physical and chemical methods of fiber modification. The operation of a paper machine is described. Methods for testing paper and uses of paper products completes the course. The text for this and all the PPE courses is *Handbook of Pulp and Paper Technology* by K. W. Britt.

Another course, "Pulp and Paper Processes I", describes in detail the operation of a modern kraft pulp mill. The course is offered in the chemical

engineering school with the mechanical engineering school providing guest lectures on forestry operations. The steps in the kraft process required to convert wood into pulp are covered. Also, the kraft chemical recovery process is outlined. A description of the common bleaching steps in a kraft mill completes the course. Since most pulp mills in the Southeast use the kraft process an entire course was devoted to a detailed description of it.

The third course in the series, "Pulp and Paper

TABLE I
Courses Taught in Pulp and Paper Engineering Program

COURSE	DESCRIPTION
Survey of Pulp and Paper Technology	A survey is made of the chemistry of pulp preparation, additives, and mechanical systems used in pulp and paper manufacturing.
Pulp and Paper Processes I	A study is made of the various processes in a Kraft pulp and paper mill necessary to convert raw material into pulp. The chemical and mechanical characteristics of Kraft pulping, bleaching, and chemical recovery processes are examined in detail.
Pulp and Paper Processes II	The major pulping processes other than Kraft pulping are examined to establish a general knowledge of the various factors affecting each pulping process. The unique advantages and disadvantages of each of the pulping processes is stressed.
Paper Formation and Properties	The processes involved in the fabrication of paper and paper products from pulp are examined. The effects on paper properties of Chemical and mechanical pretreatment of pulp are demonstrated in the laboratory.
Pulp and Paper Mill Emission Control	The methods available for control of gaseous, liquid, and solid wastes from pulp and paper mill operations are surveyed. Major biological, chemical, and physical methods for treatment of waste streams and in-plant changes to prevent waste generation and increase waste by-products utilization are described.

Processes II", includes the major pulping processes other than kraft. The properties of softwoods, hardwoods, non-wood fiber sources, and secondary fibers used in these processes are described. The sulfite, both acid and neutral, semi-chemical, and mechanical pulping processes are outlined. A brief description of some of the more important non-sulfur pulping processes such as oxygen pulping concludes the course.

Following the courses dealing with the pulping of wood, "Paper Formation and Properties", which describes the processes involved in the fabrication of paper and paper products, is offered. The steps in pretreatment of the pulp prior to the paper machine are explained. The functions of the various operations in a paper machine are then described. Considerable emphasis is placed on the mechanism for coating paper and the resulting paper properties. Testing of paper and the properties and uses of paper are also covered. Guest lectures are given by faculty from textile, ceramic engineering, and architecture in the areas of pulp additives, clay coatings, and uses of paper in structures respectively.

The last course in the series is "Pulp and Paper Mill Emission Control". Several courses in water and air pollution control are offered at Georgia Tech. However, pulp and paper mills have many unique pollution control problems. The course begins with a discussion of some of the regulatory and economic constraints that limit the options in control of emissions from pulp and paper mills. A guest lecturer from the federal or state EPA Office is asked to lead the discussion. All three types of emissions—gases, liquids, and solids—are considered. While methods of treating these wastes are described, emphasis is placed on process changes that reduce or eliminate the wastes.

STUDENT OPTIONS

THE PPE PROGRAM has been structured to meet the needs of three types of students (Figure 1). The students who only need a general knowledge of the pulp and paper industry are encouraged to take the survey course. Many textile engineering students have elected to take this option. For students whose main interest is environmental engineering we recommend the survey and the emission control courses. This option has appeal primarily to civil and mechanical engineering students.

The main thrust of our program is directed at

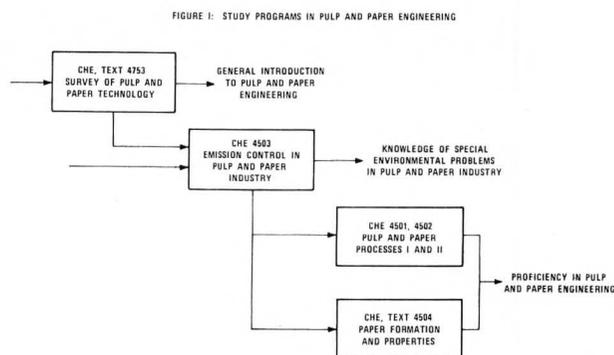


FIGURE 1. Study Programs in Pulp and Paper Engineering.

engineering students who wish to become proficient in all areas of pulp and paper engineering, with the goal being a career in the pulp and paper industry. For these students we suggest the four advanced PPE courses. If a student working toward an advanced degree (M.S. or Ph.D.) successfully completes the four advanced PPE courses and also completes an independent pulp and paper related research project, he or she is awarded a certificate of proficiency in pulp and paper engineering.

TEACHING AIDS

SEVERAL TEACHING AIDS are used in the PPE courses (Table II). The introduction of each PPE course usually consists of a brief history of the topic covered by the course and an

TABLE II
Teaching Aids used in Pulp and Paper
Engineering Courses with Student Evaluation

Educational films	2.6
Guest lectures from industry, government, and Georgia Tech. Faculty.	2.2
Plant trips to pulp and paper mills	2.4
Term paper dealing with current industry problem	1.8
Laboratory demonstrations of pulping and paper making processes.	2.6
Use of visual aids such as samples of raw materials, intermediate and finished products, wastes, etc. and a scale model of a pulp and paper mill.	2.4

KEY:

- 3.0 significantly improved quality of course
- 2.0 moderately improved quality of course
- 1.0 no improvement in quality of course
- 0 detracted from quality of course

educational film dealing with the pulp and paper industry. Normally one or two guest lectures from experts in various areas of pulp and paper are included in each course. For example, in "Pulp and Paper Processes I", an M.E. professor lectures on forest operations and usually an industry expert on some phase of kraft pulping. A plant trip is also offered to students if sufficient interest is shown. A term paper dealing with a current problem in the pulp and paper industry is required in all PPE courses except the survey course.

Other teaching aids used to make the PPE courses interesting as well as educational are laboratory demonstrations of pulping and paper making processes and visual aids such as samples of raw materials, intermediate and finished products,

The PPE program is structured to meet the needs of three types of students: those needing a general knowledge of the industry; those wishing to apply environmental engineering to the industry; and those having a professional interest in the industry.

wastes etc., and a scale model of a pulp and paper mill.

At the conclusion of each of the three PPE courses that were first taught the students were asked to complete a questionnaire evaluating the courses as a whole and the effectiveness of the teaching aids discussed above. Table II shows the student's evaluation of the teaching aids used in the PPE courses. The use of educational films, laboratory demonstrations, and visual aids received the most favorable student response. The students were slightly less favorably impressed with the guest lectures. The lower rating of the guest lectures resulted primarily from the low scores given one guest lecturer who misunderstood the topic on which he was to speak. The lowest student rating was given to the term paper requirement. Despite the relatively unfavorable student reaction, the term paper requirement will remain. It should be noted that three students, two Ch.E. and one M.E., have used the ideas generated during preparation of their term papers as the basis for graduate research.

INDUSTRY ADVISORY COMMITTEE

TO HELP EVALUATE and strengthen Georgia Tech's Pulp and Paper Engineering Program, an Industry Advisory Committee composed of in-

dustry leaders has been formed. The initial meeting of the advisory committee and Georgia Tech faculty was held at Georgia Tech in September, 1974. Many useful suggestions were made by the advisory committee which have resulted in improvements to the PPE program. Perhaps the most important development to come out of the meeting was the decision to limit the PPE program to a series of technical electives to supplement the traditional engineering training given in the various engineering schools rather than attempt to develop a formal degree program.

Other recommendations of the industry advisory included:

- Equipment for a small pulp and paper laboratory for instructional and research needs should be obtained. However, no formal PPE laboratory courses should be in-

cluded in the PPE program.

- "Real-life" problems of the pulp and paper industry should be given the students in the PPE courses for term papers, special problems, etc. These problems would be supplied by industry (no shortages anticipated).
- A continuing education program, developed in cooperation with TAPPI and other groups serving the pulp and paper industry, should be developed.

CONCLUSIONS

The pulp and paper engineering program at Georgia Tech is and will continue to be flexible. Modifications of the program will be made as needed to fit the changing needs of our students and of the pulp and paper industry. The one constant in our program is the goal of an engineer completely competent in the basic engineering fundamentals who also possesses special training in pulp and paper engineering. □

REFERENCES

- Academic Advisory Group, Technical Association of the Pulp and Paper Industry, "The Effectiveness of Pulp and Paper Schools", TAPPI, Vol. 55, No. 8, 1164 (August, 1972).
- Folger, J. K., "Future Demand for Graduate Manpower: Is Wood Science and Technology Facing a Crisis?" Presented at Annual Meeting of Society of Wood Science and Technology, Dallas, Texas, June 18, 1972.

PLUG-FLOW TRANSIENTS: Fan, Lin

Continued from page 123.

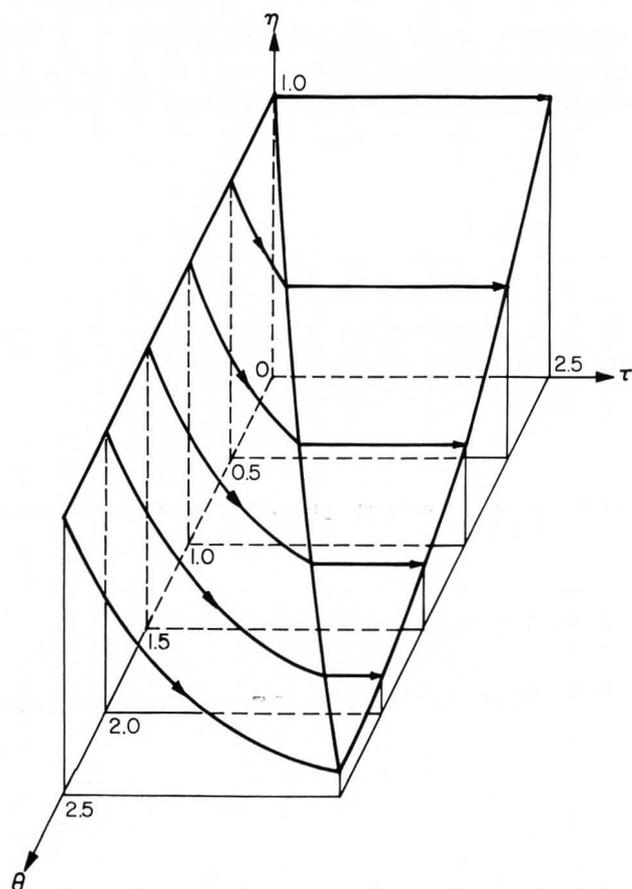


FIGURE 5. Three-dimensional concentration plot for the second example.

Elimination of A from Eqs. (20) and (25) leads to

$$\eta = e^{-(\tau-\Delta\theta)} = e^{-\theta}, \tau \geq \theta \quad (26)$$

Similarly, application of Eq. (24) to Eqs. (19) and (20) yields

$$\tau < \theta$$

and

$$1 = A e^0 = A$$

Hence,

$$\eta = e^{-\tau}, \tau < \theta \quad (27)$$

The concentration distributions represented by Eqs. (26) and (27) are graphically shown in Figs. 4 and 5. In all the figures, the numerical values are given up to an arbitrary dimensionless time and length of 2.5.

CONCLUDING REMARKS

IT CAN BE SEEN THAT for relatively simple linear systems, the solution procedure by means of the method of characteristics is straight-

forward, and the graphical interpretation of the numerical results can be very instructive. If the original first order partial differential equation is nonlinear, or if one has a set of simultaneous first order partial differential equations in hand, the analytical solution as illustrated by the two simple examples may become impossible, and more often than not, one must resort to numerical solution. Even under such a situation, numerical integration of the ordinary differential equations resulting from the application of the method of characteristics, i.e., Eqs. (6) and (7), may be more desirable than direct numerical solution of the original partial differential equation. There are two reasons for this. The first is that most of the undergraduates are sufficiently familiar only with the solution of ordinary differential operations. The second is that the numerical solutions of ordinary differential equations can always be made stable in contrast to those of partial differential equations. Many easily accessible packaged computer subroutines, e.g. CSMP, are available for the numerical solution of ordinary differential equations.

Those who are interested in the mathematical foundation and other applications of the method of characteristics should consult the references cited. □

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REFERENCES

- Abbott, M.B., *An Introduction to the Method of Characteristics*, Thames and Hudson, London (1966).
- Acivos, A., "Method of Characteristics Technique," *I&EC* 48, 703-710 (1956).
- Aris, R. and Amundson, N.R., "Mathematical Methods in Chemical Engineering," Vol. 2, *First-Order Partial Differential Equations with Applications*, Prentice-Hall, New York (1973).
- Courant, R., "Methods of Mathematical Physics," Vol. 2, *Partial Differential Equations*, Wiley-Interscience, New York (1962).
- Lapidus, L. "Digital Computation for Chemical Engineers," McGraw-Hill, New York (1962).
- Liu, S.L., Aris, R. and Amundson, N.R., "Stability of Non-adiabatic Packed-Bed Reactors," *I&EC Fundamentals*, 2, 12-20 (1962).
- Perry, R.H. and Chilton, C.H., *Chemical Engineers' Handbook*, 4th ed., McGraw-Hill, New York (1973).



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