

# CHE

## chemical engineering education

VOLUME XVII

NUMBER 2

SPRING 1983



CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

**JOHN A. QUINN  
OF  
PENNSYLVANIA**



*3M Award Lecture*

• INPUT MULTIPLICITIES IN PROCESS CONTROL •  
Lowell B. Koppel

Reference States and Relative Values of Internal Energy, Enthalpy, and Entropy  
A. G. FREDRICKSON

Laboratory Experiment for the Transient Response of a Stirred Vessel  
R. D. NOBLE, R. G. JACQUOT, L. B. BALDWIN

Infusion of Socio-Humanistic Concepts into Engineering Courses  
CHARLES HUCKABA, ANNE GRIFFIN

Distillation Calculations with a Programmable Calculator  
CHARLES A. WALKER, BRET L. HALPERN

ChE Education in the Third World—Two Views  
P. L. SILVESTON, H. K. ABDUL-KAREEM

*and*

ARIS: Ballad of Jack Weikart

**CHE AT DELFT UNIVERSITY**

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## *John A. Quinn* of Pennsylvania

EDUARDO D. GLANDT AND  
DOUGLAS A. LAUFFENBURGER  
*University of Pennsylvania*  
*Philadelphia, PA 19104*

**T**HE YEAR 1983 MARKS 25 years in the teaching profession for John A. Quinn, the Robert D. Bent Professor and Chairman of the Department of Chemical Engineering at the University of Pennsylvania. Coincidentally, he has also graduated his 25th PhD student this year, and therefore it seems appropriate to reflect on his career in chemical engineering education and research.

Although he now finds himself comfortably at home on Philadelphia's Main Line, John was raised in the midwestern heartland, in Springfield, Illinois. After graduating from the University of Illinois in 1954, he went east to Dick Wilhelm's chemical engineering department at Princeton for graduate work. His PhD thesis work on fluidization was supervised by Joe Elgin, and by Leon Lapidus upon Elgin's ascension to the post of Dean. During those years, John learned the joys of commuting through frequent trips to Bryn Mawr, just outside Philadelphia and not far from his present home, to visit his fiancée. He and Frances were married at the completion of his degree, and they headed back to Champaign-Urbana where John rejoined his alma mater as assistant professor in 1958. Promotion to associate professor came in 1964 and to full professor in 1966.

The department at Illinois was then under the leadership of Harry Drickamer who, along with

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**... John was recognized by election to the National Academy of Engineering in 1978. In the same year he received the Alpha Chi Sigma Award from the AIChE.**

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Wilhelm, Elgin and Lapidus, are recognized by John as the major influences on him in his developing years as a researcher and teacher. Moving away from fluidization as a field of study, he began a program of inquiry into unexplored territory in interfacial transport phenomena, which he has continued to this day. John's early work in this area earned him the Allan P. Colburn Award in 1966, for excellence in publications by a young AIChE member. Not long after, his stay at Illinois was interrupted by what he likes to call a "pleasant interlude" on sabbatical at Imperial College in London. Beyond this brief description, he is slightly vague when junior faculty members ask about how research ideas are generated during a sabbatical leave.

In 1971, Art Humphrey, then department chairman at Penn, succeeded in attracting John to join his faculty. In this, John followed the path of Dan Perlmutter who had come from Illinois to Penn a few years earlier. John's addition had great impact on the growth of the department, both

through his teaching and his research. Within three years from his arrival, his classroom excellence was recognized with the S. Reid Warren Award for distinguished teaching. Four years later, he was chosen to be the first incumbent of the Robert D. Bent Professorship, established at Pennsylvania by the Atlantic Richfield Foundation. The Bent chair seems singularly appropriate for a man of the stature of "Big John" (as he is affectionately, but discreetly, known by the staff).

The experimental research program in interfacial phenomena carried out by John and his series of students (five currently in residence) has followed several avenues. In the early years, a major portion of this careful work dealt with thin liquid films, monolayers, and Marangoni effects. Later, closely related efforts included studies of jet-drop fractionation. Another important line of investigation is concerned with membrane transport phenomena. John and several of his students, John Anderson (now at Carnegie-Mellon) among them, pioneered the use of track-etched mica mem-



**Despite being chairman, John gets much of his satisfaction from his active research program. Here he is shown with Patricia Rodillosso, one of his PhD students, in the interfacial transport laboratory.**

branes as a powerful tool for learning about equilibrium and transport phenomena in pores. In addition, John has studied nonporous and natural membranes, making significant advances in the understanding of carrier-mediated and active transport. The conception and development of compact "membrane reactors," consisting of the juxtaposition of catalytic and semipermeable layers, capable of performing chemically-driven separations or of forcing thermodynamically unfavorable reactions is a major advance in the technology of membrane applications. This area, which



**This gathering of his graduate students (with spouses and friends) at the Quinns for Christmas typifies the warm relationships John establishes with those who work with him.**

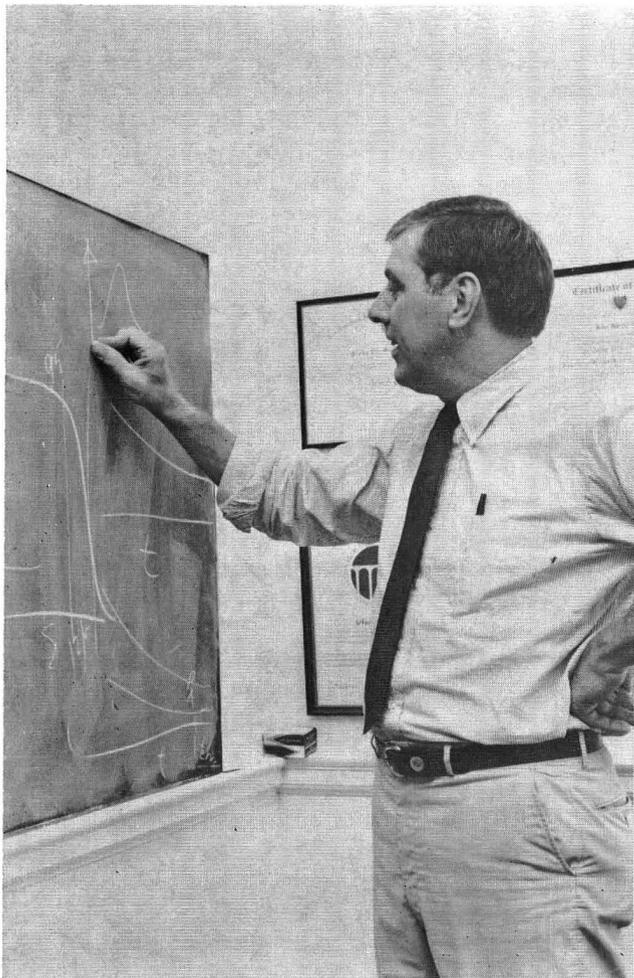
grew out of the thesis research of one of John's recent PhDs, Steve Matson, is now being hotly pursued. For his long list of novel research contributions, John was recognized by election to the National Academy of Engineering in 1978. In the same year, he received the Alpha Chi Sigma Award from the AIChE, for outstanding chemical engineering research. Among many other honors, he was the Sixth Mason Lecturer at Stanford in 1981.

While much of the aforementioned research work has relevance to biological systems, other projects he has been involved with have had even stronger connections with biology and medicine. Among them, in collaboration with David Graves of the Penn chemical engineering faculty, is the investigation of transport of gases through skin, with applications to oxygen supply by the micro-circulation, prevention of decompression sickness, and analysis of gas concentration in the blood for clinical purposes.

Since chemical engineering at Penn has traditionally been strong in biochemical and biomedical applications, it is not surprising that John's research interests are often labelled as "bioengineering." He is very careful, however, when asked to identify this as his distinct area of work, and is quick to explain the role that it must play within the chemical engineering profession. An analogy often heard from him is to modern electrical engineering, a discipline that succeeded in providing wonders like hand-held calculators and mini-computers because its practitioners were aware of the advances in solid-state physics and were ready to

use them. John feels that chemical engineers should at the present time be carefully observing the developments in biochemistry and biophysics. An engineer can choose either to help understand the ways by which nature carries out chemical reactions so beautifully, or to exploit such understanding to new benefits. He has focused on the latter goal, and his membrane reactors are a superb example of his philosophy: "All engineering disciplines prosper as they are linked to a basic science."

John particularly enjoys reminiscing on the evolution of chemical engineering education and the chemical engineering profession, preferably over a cold Rolling Rock. His early career took place during the "golden sixties." Not only was this a time of rapid growth for scientific and technological programs in academia, but he will point out that it also was a turning point for research in chemical engineering. Chemical engi-



**John is highly popular with the students for the clarity and enthusiasm of his teaching.**

---

**... his membrane reactors are a superb example of his philosophy: "All engineering disciplines prosper as they are linked to a basic science."**

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neers, once and for all, ended the impression that their research consisted of outmoded chemistry. John is apt to emphasize that chemical engineers of today are capable of doing scientific research as well as those in any chosen field. Contributions by chemical engineers in fluid mechanics, for example, are now cited by all fluid mechanics. The same goes for surface chemistry, as another example. Chemical engineers can now work on the fundamental, as well as on the applied, aspects of science, without any self-imposed limits. One of John's favorite phrases is "chemical engineering is what chemical engineers do."

This philosophy has guided John's leadership role at Penn, particularly since he accepted the chairmanship in 1980. He is a great encouragement to faculty pursuing research in areas that stretch beyond the traditional boundaries once supposed to encircle the discipline of chemical engineering. The overriding principle is that whatever is undertaken, the goal should be to perform at the pioneering edge of the chosen field.

Chairmanship of a department is usually accepted under protest, and John is no exception to this rule. "To enjoy being a chairman", he says, "you must get your kicks from seeing other people do well." This is undoubtedly true in his case, for he takes pride and pleasure in any accomplishment of his colleagues, especially the younger ones. Yet he still gets much of his satisfaction from his own research and teaching. Accordingly, John has exhibited an administrative style which relies heavily on delegating responsibilities. We had been given notice of this attitude when, immediately after becoming chairman in the summer of 1980, he went away for a half-year mini-sabbatical at the Woods Hole Laboratory and at MIT. The motivation for those blessed with various duties is certainly linked to John's admirable leadership qualities. However, he will frequently claim that the effect of a chairman on his department is highly non-linear, meaning to emphasize that there is a saturation effect after some time, and that rotation of the position is healthy. This doesn't fool us, though, being the same old protest dressed in engineering language.

It is easy to catch John's enthusiasm for the future of chemical engineering at Penn. He har-

bors no doubts about the role of engineering at an Ivy League university, especially given the long tradition of interaction with the various physical and life science departments here. He enjoys emphasizing that it is an ideal place for remaining closely linked to the basics, and therefore is "fertile

ground" for marshalling a first-rate research and teaching program. It is clear that we are also extremely fortunate to have "Big John" (protocol being temporarily suspended here) as our marshal. □

## **ChE** stirred pots

# **BALLAD OF JACK WEIKART**

by *Rutherford Aris*

Editor's Note: The following ballad was read by Prof. Aris in the Exxon suite at the 1983 AIChE annual meeting. CEE joins the academic community in saluting Jack on his retirement from Exxon.

*Jack Weikart was a citizen  
Of tact and of rapport.  
An Exxon captain eke was he  
From Jersey's eastern shore.  
When Exxon wished to fill its ranks  
Or its largesse bestow  
They called for Jack, the chap with knack,  
The man most in the know.  
Whether the good ol' D. of E.  
Were pulling back on shale,  
Or Exxon'd made discovery  
Beyond the farthest pale,  
Whether the stocks of gasoline  
And oil were running low,  
Or whether shieks of Araby  
Had dealt their latest blow,  
Whether the oil profits drew  
Apologetic coughs,  
Or whether they turned negative  
In Reagonomic troughs,  
The Admirals forth their captain sent  
To fetch a Chem E. crew.  
They said to Jack, "You bring 'em back  
We know what you can do."  
So out would come Jack's little book  
In which he kept the tot  
Of which was where, and who was who,  
And who was doing what.  
Then off he'd go as was his wont  
To cull each Inst. and U.  
Sometimes he wanted all the crop  
And sometimes precious few.  
But stay! Though Jack is truly tops  
At the recruiting game*

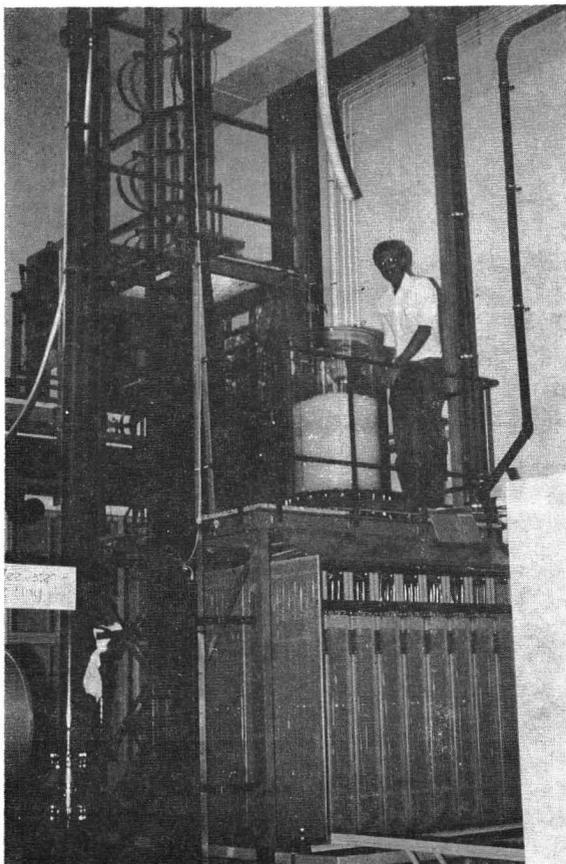
*That is not all; he has, you know,  
Another claim to fame.  
Whenever A.I.Ch.E.s  
In learned conclave meet  
Our Jack you'll find dispensing cheer  
Within the Exxon suite.  
For oft—with Peg—he has reserved  
A penthouse in the sky,  
Four-poster bed, plush carpeting  
And mirrors set on high.  
And from the living room of such  
A truly classy job,  
With wine & beer & sundry drinks,  
He entertains the mob  
Of academic types who swarm  
Until the place near bursts  
With shouting profs all trying to slake  
Their monumental thirsts.  
(For word is passed from prof to prof  
As each one registers,  
"Psst. Write this number on your card  
Before your vision blurs.  
The Exxon suite's a perfect square,  
Its digits four are too,  
What's more it is the least of such  
And has a splendid view.")  
O'er all our Jack—and with him Paul—  
Preside with great panache,  
And woe betide industrial types  
If they should try to crash!  
For Exxon suites are sacred as  
The groves of Academe;  
There hiring's done, ideas are swapped  
And hatched is many a scheme.  
Oh, woe are we, no more to see  
Jack Weikart's hoary head,  
And hear him boom across the room,  
"Time's up! Be off to bed."*

*Sail on! Sail on! Exxon. Exxon.  
You'll never see, alack,  
For fetching you a Chem E. crew  
As mighty a man as Jack.*

## DELFT UNIVERSITY OF TECHNOLOGY

JULIA E. LITTLE  
*Virginia Polytechnic Institute  
and State University  
Blacksburg, VA 24061*

**A**RE YOU TRYING TO locate lecture room 123? This may be relatively easy at an American university, where all you need do is differentiate the many classrooms by their room numbers. But at the Delft University of Technology in Delft, The Netherlands, your predicted easy search for room 123 will instead lead to your wandering about the Scheikundige Technologie (Chemical Engineering) building. You will observe laboratory upon laboratory, but not many classrooms with desks and blackboards. You may not realize it at the



**A large reactor located in the Physical Technology laboratory, one of the required laboratories for 3rd and 4th years.**

time, but you are seeing classrooms, because at Delft, the laboratory itself is a classroom.

I had the unique opportunity to discover the organization and activities of the Delft Chemical Engineering and Chemistry Department as an exchange student participating in the International Association for the Exchange of Students for Technical Experience (IAESTE) program. Through my discussions with twelve members of the department—professors, graduate students, laboratory technical staff, and a program coordinator—I was able to translate departmental documents and catalogues, compiling an informational report on the educational experience at the Delft University of Technology.

Chemical engineering and chemistry are combined into a single department at Delft, so there are no “pure” chemistry majors or chemical engineering students. The department is sub-divided into the following ten workgroups:

- Chemical Engineering
- Organic Chemistry
- Analytical Chemistry and Laboratory Automation
- Inorganic and Physical Chemistry
- General Chemistry
- Biochemistry
- General and Applied Microbiology
- Biochemical Reactors
- General and Technical Biology
- Technical and Macromolecular Systems

This particular combination of so many fields has a historical basis in the Delft fermentation industry and in the production of rubber, tea, and coffee in the former Dutch colonies.

The department currently has 430 employees

- 16 full professors
- 6 associate professors
- 120 academically-degreed professionals, of which 80 are tenured research associates
- 40 non-permanent graduate students
- 290 technicians, secretaries, and service employees

Each of the sixteen professors typically has two staff members, several graduate students, and a varying number of fourth- and fifth-year stu-

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**In addition to the six different required laboratories, two research projects initiated by current research being performed by a professor, or by some aspect of a Ph.D. project, are required.**

dents working with him. Professors are highly respected and highly paid (\$50,000 per year) for conducting research, teaching, and representing the department through international travel, seminars, and industrial contacts.

Approximately 130 new students enter the department each year. Because forty percent of these students do not pass the Propaedeutic Examination after the first year, only approximately 55 students graduate per year. Considering only the full professors, the student-to-faculty ratio is 31:1. However, because of the academically-degreed professionals, the tenured research associates, and the graduate students, who also teach courses and instruct laboratories, the student-to-teacher ratio is closer to three students per "teacher." There is sufficient space for all: the professors, staff, and students in the ten workgroups have their laboratories located in four large chemical engineering and chemistry buildings.

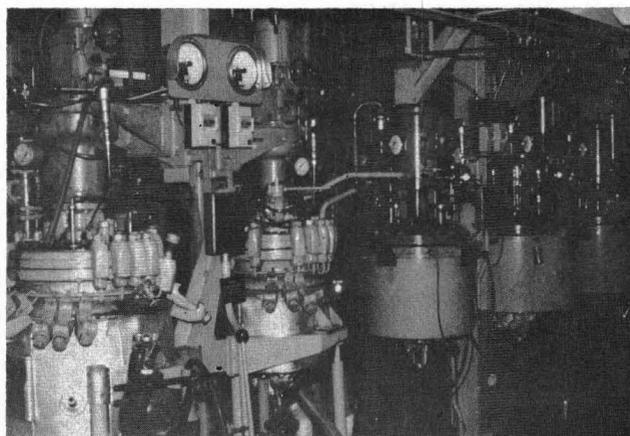
The state government completely finances the Delft University of Technology with the exception of some research money from the research foundation Z.W.O. and less than one percent from industry. The students pay very little for their university education: only f900, or \$360, per year. In addition, for many students cost of living expenses are provided by the government in the form of interest free loans. Because of the huge sums of money invested in Delft by the government during the past fifteen to twenty years, the university is a showcase of technology for The Netherlands.

In the Chemical Engineering and Chemistry Department, a lump sum from the government pays wages, equipment costs, travelling expenses, and other operation expenses. During the 1980 fiscal year, this sum amounted to approximately 2.25 million dollars. This figure does not include salaries, however, because the state pays the staff as civil servants directly. Salary costs were approximately \$12.5 million in 1980. The chemical engineering workgroup received 24% of all the funds that were divided between the ten different work groups during the 1980 fiscal year.

Because of government reluctance to continue increasing its expenditures for higher technical education, more pressure is now being placed on

researchers to obtain research funds from industry. For the 1982 fiscal year the department will receive approximately fifty percent of that received in the past to finance equipment costs, and expectations for future years are not very good. Also, the government has required a reduction in the duration of study programs from five years to four years starting in September 1982. Students will have "student" status only for six years.

The present five-year study program leads to the title Chemical Engineer for a student who passes the Propaedeutic examination, the Candidate's examination, and the Final Engineer's ex-



**Small scale production and control of a process forming catalyst consisting of an alloy on a carrier, located in the Process Technology laboratory.**

amination. The first two years are identical for all students, whereas the last three years are referred to as the "free study", during which time a student specializes in one major field and one minor field. Because the study program lasts for five years—with the fifth year devoted to research—the degree obtained from Delft is more similar to the M.S. chemical engineering degree from an American university.

The new four-year study program—began September 1982—is very similar to the present five-year program. The only fundamental changes are a reduction in the credits associated with the research project, design project, and literature study, and the inclusion of such work in the fourth year. Table 1 gives the proposed curriculum, which can now be directly compared with the four-year chemical engineering programs in the United States. Note that semesters at Delft last for thirteen weeks, and that course credits are designated as "c.p. units", where 1 c.p. unit equals approximately 40 hours.

From my observations, Dutch students work very hard in high school, and enter the university at a higher level than do students in the United States (perhaps with the equivalent of a year of college in the U.S.). Once they enter the university, the question of student attitudes and motivation can be raised. Many students take it easy, typically completing the five-year chemical engineering program in six to seven years, for example.

One reason why the chemical engineering study program requires more time is the number of required laboratories. A more important reason is that students take their final examinations only twice a year, and not necessarily immediately following the end of class lectures. This delayed examination schedule lends itself to class cutting and the postponement of studying until several weeks before the yearly exams. But the chemical engi-

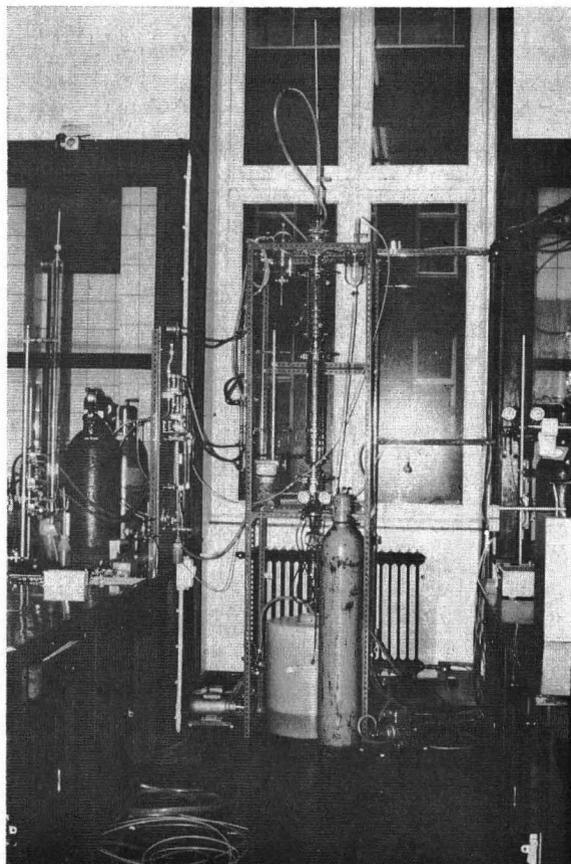
neering students are not an exception. While the average chemical engineering student completes his five-year program in six to seven years, the average student at Delft finishes his five-year program in seven to eight years, with architecture students finishing typically in nine years.

The most outstanding quality I encountered in all of the students that I met was their realization of the importance of research, both to gaining new knowledge and applying this knowledge to current problems. The students are thinkers and innovators, mainly because of Delft's emphasis on open-ended research, challenging student projects, and laboratory experience.

Because Delft considers laboratory experience and research to be such an important part of a complete chemical engineering education, attention should be drawn to the outstanding facilities and

TABLE 1

FIRST YEAR		THIRD YEAR	
	c.p. units	1st Semester	
<b>1st Semester</b>			
Mathematics I	3	Automation	2.5
Mechanics of Solids and Fluids	3	Process Design	2.5
Inorganic Chemistry	3	Analytical Chemistry	2.5
Organic Chemistry	3	Environmental Studies	2
Quantum Chemistry	2	System Modeling	2.5
Technical Writing	1	Elective	2.5
	<u>15</u>		<u>14.5</u>
<b>2nd Semester</b>		<b>2nd Semester</b>	
Mathematics II	3	Polymers	3.5
Computer Programming	2.5	Industrial Chemistry	2.5
Transport Phenomena	2.5	Process Equipment	2.5
Thermodynamics	4	Product Technology	2.5
Bioscience I	3	The Chemical Plant	2
	<u>15</u>	Elective	2.5
			<u>15.5</u>
<b>First Year Laboratories</b>		<b>Second and Third Year Laboratories</b>	
(divided over both semesters)		Physics	2
Chemistry (IR, UV, AAS, GLC)	8	Methodology	.5
Physics	2	Basic skills in:	
Chemistry and Society	1	Organic Chemistry	3
Excursions to Industry	1	Inorganic & Physical Chemistry	3
	<u>12</u>	Biosciences	3
		Automation	3
<b>SECOND YEAR</b>		Physical Technology	3
<b>1st Semester</b>		Process Technology	3
Mathematics III	4	Research Project	2x 3
Phase Equilibria	3		<u>24.5</u>
Kinetics	2	<b>FOURTH YEAR</b>	
Separation Processes	3	Electives (3)	3x 3
Physical Chemistry	3	Industrial work	7
	<u>15</u>	Literature study & report	6
		Design Project	6
<b>2nd Semester</b>		Research Project & paper	20
Statistics	4		<u>43.5</u>
Particle Technology	2.5		
Reactor Design	3.5		
Organic Chemistry II	2.5		
Bioscience II	2.5		
	<u>15</u>		



**Absorption apparatus for second year project #47, Removal of CO<sub>2</sub> from process gases.**

program the department has developed.

First year laboratories stress development of good experimental and research techniques, thoroughness, and report writing ability. One laboratory located in the Propaedeutic Chemistry building is devoted solely to gas-liquid chromatography and infrared equipment for first-year students. An assistant specialized in analytical techniques is responsible for this GLC/IR laboratory. During the first week, the chemistry laboratory reviews high school techniques. Twelve to fourteen inorganic and physical chemistry laboratory experiments follow during the next twenty-three weeks, scheduled during Thursday and Friday mornings (9 a.m. to 12:30 p.m.) and afternoons (1:30 p.m. to 5:15 p.m.). During the second semester, six or seven organic laboratory experiments are completed. Thus, during the first year a total of eighteen to twenty experiments in organic, inorganic, and physical chemistry are conducted, with each experiment having a duration of approximately six to ten hours.

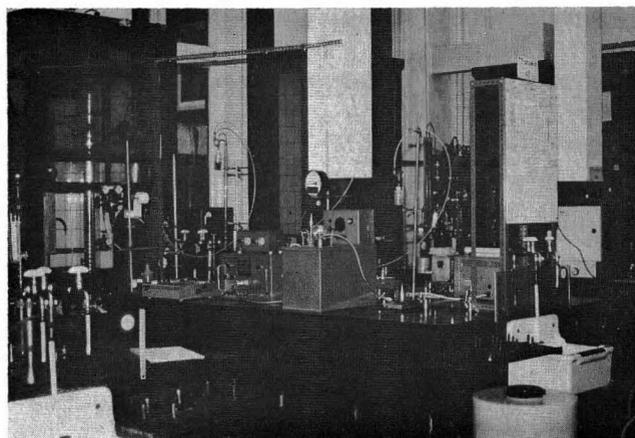
The typical laboratory experience is much more than one of just following, step by step, a standard

university experiment handbook. To perform an experiment, a student, working individually, must get an outline from one of the two laboratory assistants (there is one laboratory assistant for every ten students). The student must first review the cited literature, then speak to the lab assistant privately and answer preliminary questions that he may raise. If the student is adequately prepared, he is allowed to set up his apparatus. This process of setting up usually takes an entire morning, or at most, an entire day. The laboratory assistant must then approve the apparatus before the student can begin the experiment. The data, results, and theoretical post-experiment questions are handed in for grading in very concise form. Longer reports are written only three or four times per year.

While the first-year and most of the second-year laboratories are located in the Propaedeutic Chemistry building, some of the second- and all of the third-year physics and methodology laboratories and the basic skill laboratories in organic chemistry, inorganic and physical chemistry, bio-science, automation, physical technology, and process technology are located in different work-group laboratories.

In addition to the six different required laboratories, two research projects initiated by current research being performed by a professor, or by some aspect of a Ph.D. project, are required. The general reasons for having these projects are to have students learn to cooperate and to distribute work among themselves, to stimulate research interest, and to combine several different study

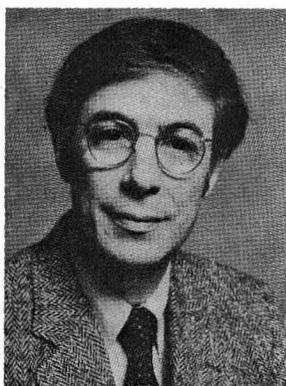
Continued on page 92.



**Following the absorption of CO<sub>2</sub>, shown above, the CO<sub>2</sub> is desorbed. Recovery concentrations and measurements are made with the analysis equipment shown.**

## Award Lecture

# INPUT MULTIPLICITIES IN PROCESS CONTROL



The 1982 Chemical Engineering Division Lecturer is Lowell B. Koppel of Purdue University. The 3M Company provides financial support for this annual lectureship award.

Born and raised in Chicago, Lowell graduated with the B.S. from Northwestern University in 1957, the M.S. from the University of Michigan in 1958, and the Ph.D. from Northwestern in 1960.

His interest in process control began in 1954 when he was a co-op student working as an operator's assistant in pilot plants, and his academic involvement with the subject began in 1960 when he started teaching the undergraduate process control course at Caltech.

He began teaching at Purdue in 1961, and teamed with Don Coughanowr to write an undergraduate textbook on process control. Most of his work was in the general area of developing control theory for application to processes typical of the chemical and petroleum industry. He accepted the position of head of the school in 1973 and served in that capacity until 1981 when yearnings for full-time concentration on teaching and research drew him back to the classroom.

Current research interests are focused on multivariable systems, and particularly on the effects of input multiplicity. Although he has taught virtually every required course in the curriculum, his teaching emphasis is on process control. A secondary area of interest is process design, which he views as a subject intimately related to process control, and a rapidly developing interest in interactive computer graphics. Avocations include music, hiking, and books of all sorts.

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LARGE MULTIVARIABLE PROCESS control systems sometimes contain a small number of loops which are sporadically troublesome. These loops operate satisfactorily most of the time, but periodically suffer sudden and unexplained reduction in their level of stability. The reduction is sometimes observed as excessively oscillatory transients following disturbances, and is corrected by retuning. It has also been observed as a relatively sudden change from stable to unstable operation, requiring that operating personnel remove the offending loops from automatic operation, allow the plant to settle down, and then reclose and retune the loops.

It is often hypothesized that the cause of the behavior is a gradual change in one or more plant characteristics, causing changes in the process dynamics, which in turn render the control tuning less stable. A typical example of such a characteristic is catalyst activity. There are three pieces of evidence, in my experience, which are not consistent with this hypothesis. First, the change in stability level is too sudden, and too large. Second, when the loops are opened, and retuned to bring the process back under control, the new controller settings are often not significantly different from those which were in effect when the destabilization occurred. And yet, the stability level is returned to normal by the "retuning." Finally, I have never observed the consistent pattern of movement in controller settings which one would anticipate if the cause were a unidirectional phenomenon such as catalyst decay or heat exchanger fouling.

An hypothesis which is not inconsistent with this evidence is that the plant has moved relatively suddenly to a new steady state, at which the control system is significantly less stable. However, the integral (reset) action used in the great majority of process control loops implies that any new

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steady state cannot involve new values of the output variables, *i.e.*, the variables being regulated by the control loops. These can come to rest only at the set-point values. If there is a new steady state, it has to be in the values of the input, or manipulated variables.

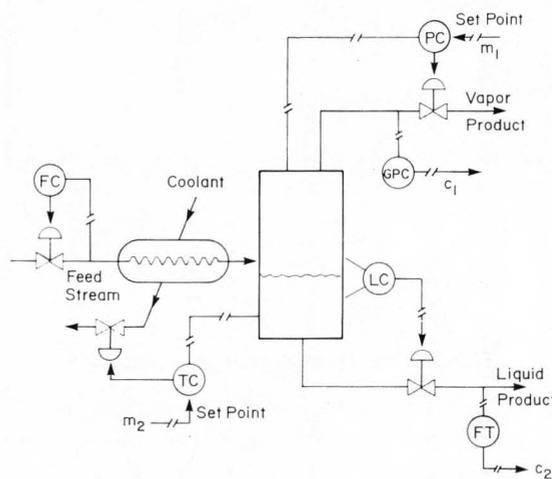
The phenomenon of multiple steady states is of general concern in chemical engineering, and there is much current research on the subject. From the viewpoint of process control, this previous research has assumed that a given set of manipulated inputs can produce more than one output at steady-state. This will be called output multiplicity. For example, the classic work by Aris and Amundson [2] shows that a given flow rate of coolant to a stirred exothermic reactor can lead to three different steady state temperatures. A likely control system for this process will manipulate the coolant flow to regulate the temperature at some desired set point value. In most cases, reset (integral action) will be used in the controller. This prevents any temperature but the desired set point value from being a steady-state. The control system has effectively eliminated the steady-state multiplicity.

However, if more than one coolant flow could produce the same reactor temperature, we would then have input multiplicity. The control system, even with reset action, could conceivably come to steady state at any of these coolant flow rates, and therefore does not eliminate the steady-state multiplicity.

The research described here investigates the potential effect of input multiplicity on multivariable chemical process control systems. Several simple processes are first shown to exhibit the possibility of input multiplicity. Some effects of the multiplicity on control systems for these processes are then illustrated by example. Finally, I will discuss recent theoretical developments on input multiplicity and closely related phenomena.

**EXAMPLES OF SYSTEMS SHOWING INPUT MULTIPLICITY**

**Flash Separator.** The process is sketched in Fig. 1. It involves isothermal flash separation of a four-component equimolar mixture. Each component is assumed to obey Raoult's law, the ideal gas law, and Antoine's equation. The manipulated inputs



**FIGURE 1. Flash separation process**

are the temperature and pressure of the flash. The outputs to be regulated are the mole fraction of component 3 in the vapor product, desired at 0.4, and the molar split of the feed into liquid and vapor products, desired at 50-50. For the following set of Antoine constants

Component	A	B
1	1000	8
2	2000	13
3	1200	11
4	476	6.09

where

$$p = \exp\left(\frac{-A}{T} + B\right)$$

with p and T in arbitrary units, the following three steady states exist

Pressure	Temp.	Mole Fraction of 3 in Vapor	Fraction of Feed Going to Liquid
$m_1$	$m_2$	$c_1$	$c_2$
196	277	0.400	0.500
275	300	0.400	0.500
750	400	0.400	0.500

For clarity, we are regarding the set points of the cascaded pressure and temperature loops to be the manipulated variables, but the same observations result if vapor draw-off rate and coolant flow rate are regarded as  $m_1$  and  $m_2$ . A control system

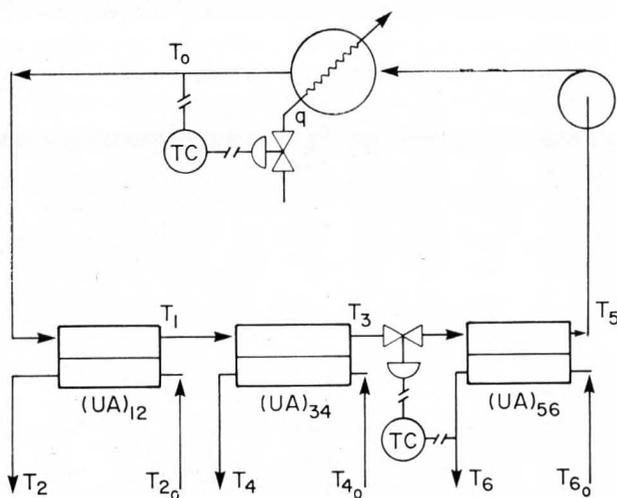


FIGURE 2. Heat exchanger process

designed to hold  $c_1$  at 0.400 mole fraction, and  $c_2$  at 50% of the original feed, has three different ways to do it, and steady-state could be reached at any of them by a control system containing reset action.

**Heat Exchange Network.** The process, containing three process heat exchangers and a utility heater, is sketched in Fig. 2. The flow rate of the utility stream is manipulated to regulate at  $487.5^\circ$  the temperature  $T_5$  of the heated stream leaving the third process exchanger. The utility heater regulates  $T_0$  at  $556^\circ$ . The utility stream heats the first process stream in the first exchanger, recovers heat from the second process stream in the second exchanger, and heats the third process stream in the third exchanger. For ease of illustration, the exchangers have been modelled as lumped, or perfectly mixed, on each side. However, precisely the same effect can be demonstrated for a network modelled with the more usual log-mean driving forces.

For the following parameter values (in any internally consistent set of units)

$$\begin{array}{lll} UA_{12} = 100 & UA_{34} = 100 & UA_{56} = 10 \\ T_{20} = 80.5^\circ & T_{40} = 665.8^\circ & T_{60} = 450^\circ \\ wCp_2 = 10 & wCp_4 = 10 & wCp_6 = 5 \end{array}$$

there are three values of  $wCp_0$  for the utility stream which will satisfy the control system. The corresponding steady states are

$wCp_0$	$T_0$	$T_1$	$T_2$	$T_3$	$T_4$	$T_5$	$T_6$
1	556.4	127.6	123.4	612.5	617.4	487.5	475.0
6	556.4	269.7	252.5	508.3	522.6	487.5	475.0
25	556.4	429.5	397.7	492.5	508.3	487.5	475.0

**Structure-Dependent Multiplicity.** There is clearly a fundamental difference between the type

of multiplicity exhibited by the flash separator, and that by the heat exchange network. The latter is structure dependent. It occurs because the temperature  $T_3$  of the hot stream entering exchanger 3 decreases as more flow is demanded by the control system on this exchanger. This behavior could not occur in a heat exchanger without the rest of the process, in this case without the action of the first two exchangers. In contrast, the flash separator exhibits input multiplicity independently of its interconnection with other process units. This difference in type of multiplicity may be important in dealing with the phenomenon.

**Sequence of Reactors.** Another example of structure-dependent input multiplicity occurs in the work of Kubicek et al. [9]. A sequence of two stirred reactors, with the exothermic reaction  $A \rightarrow B$ , was studied by these authors for output

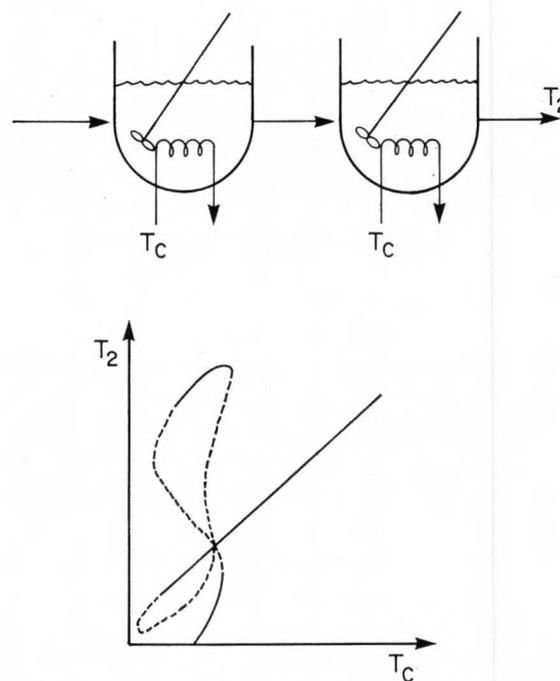


FIGURE 3. Two-reactor sequence

multiplicity. The process and its steady-state behavior are sketched in Fig. 3. A given coolant temperature used in the two reactors could produce several different steady-state temperatures of the product stream leaving the second reactor. However, examination of their plot (see Fig. 3) also shows that a given product stream temperature could be produced by as many as three different coolant temperatures. This input multiplicity has not been observed for a similar reactor ( $A \rightarrow B$ ) operating singly, suggesting again that

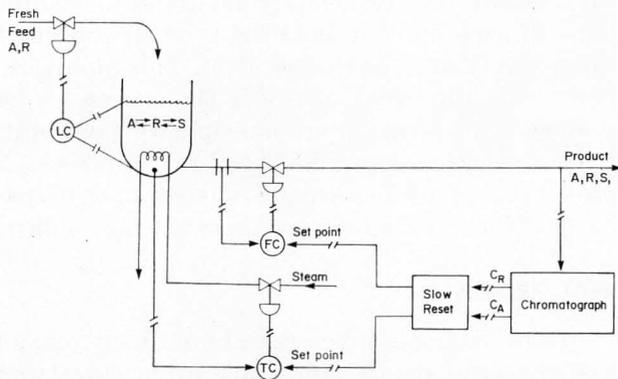


FIGURE 4. 2 x 2 reactor control scheme

process structure can play an important role in input multiplicity.

**Single Exothermal Reversible Reactor.** In a previous paper [7] a single exothermal reactor, in which the kinetics were of the form  $A \rightleftharpoons R \rightleftharpoons S$ , was shown to exhibit input multiplicity. The process is sketched in Fig. 4, and the multiplicity behavior in Fig. 5. The 2 x 2 control scheme involves manipulation of reactor temperature and residence time to regulate two of the product concentrations,  $c_A$  and  $c_R$ . Fig. 5 illustrates the input multiplicity by showing that contours of  $c_A$  values between 0.53 and 0.55 will thrice intersect the contour for  $c_R = 0.35$ . This corresponds to three sets of residence time and temperature values which will yield steady state at, for example,  $c_A = 0.54$ ,  $c_R = 0.35$ . This shows that more complex kinetics can produce input multiplicity in a single reactor, without structure dependence.

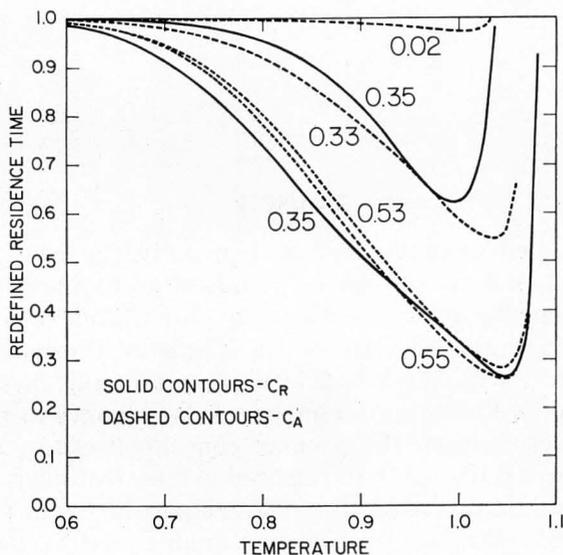
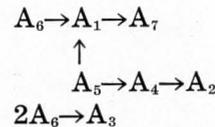


FIGURE 5. Multiple steady states in 2 x 2 control system

The input multiplicity in this case occurs in part because of the chosen temperature dependence of the kinetics. Fig. 6 illustrates this point, and shows that the input multiplicity would likely be anticipated before the control system is designed. In the next case, this is not likely.

**Single Isothermal Reactor.** In his Ph. D. dissertation, Rickard [10] studied the six-component reaction network



with mass-action kinetics. The reaction is conducted in a single, well-stirred, isothermal reactor. The 3 x 3 control system manipulates the concentrations of  $A_5$  and  $A_6$  in the feed, and the residence

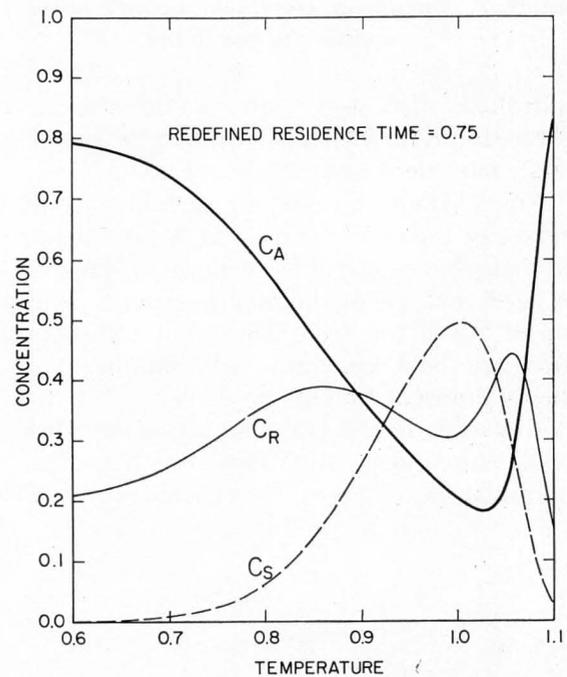


FIGURE 6. Open-loop cross plot shows input multiplicity possibility

time, to control concentrations of  $A_1$ ,  $A_2$ , and  $A_3$  in the product. It is thus similar to the one sketched in Fig. 4. Rickard demonstrated input multiplicity by exhibiting three different sets of the three manipulations which will produce the desired set of three exit concentrations. This example differs from the previous one primarily in being of higher dimension. However, it is introduced because it also has been shown to exhibit an unconstrained limit cycle, which is an important aspect of input

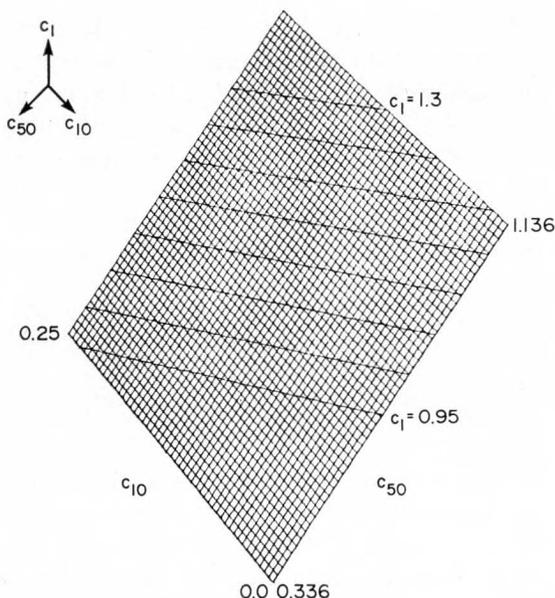


FIGURE 7. Open-loop cross plot doesn't show input multiplicity possibility

multiplicity discussed below, and because detection of the input multiplicity cannot be based on a simple parametric plot such as Fig. 6.

Fig. 7 [10] illustrates one such plot. It shows a surface of the concentration of  $A_1$ , plotted against the disturbance variable, concentration of  $A_1$ , in the feed, and one of the manipulations, concentration of  $A_5$  in the feed. The other two manipulations are held constant. All similar plots are equally innocent for this process.

However, Fig. 8 [10] shows the same behavior under closed-loop conditions for the other two manipulations. That is, the concentration of  $A_6$  in

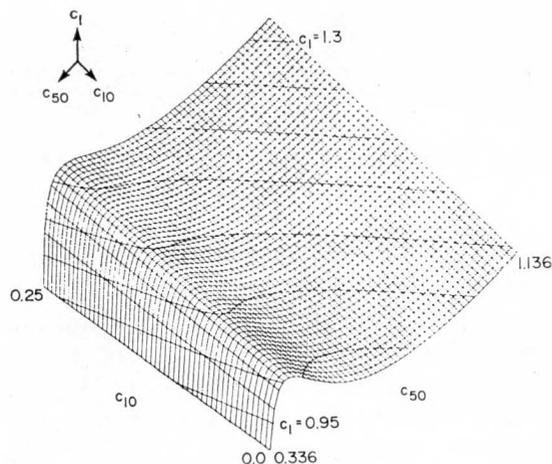


FIGURE 8. Closed-loop cross plot needed to show input multiplicity possibility

the feed and the residence time are both manipulated at each point to hold the product concentrations of  $A_2$  and  $A_3$  at the set point. This plot, which represents the behavior under the chosen control system, shows the input multiplicity possibility. Such plots are seldom made for real processes, in part because of inadequate models and in part because the calculations are almost always difficult.

## REAL PROCESSES

These example processes are quite simple, and the alternate steady states are often catastrophically removed from each other. Typical chemical processes are far more complex, and should be capable of exhibiting this phenomenon at more closely spaced steady states.

## POSSIBLE PROCESS BEHAVIOR UNDER INPUT MULTIPLICITY

**Divergence to Alternate Steady State.** Input multiplicity is of concern in process control because the multiple steady states are not eliminated by the control system. Therefore, one obvious pos-

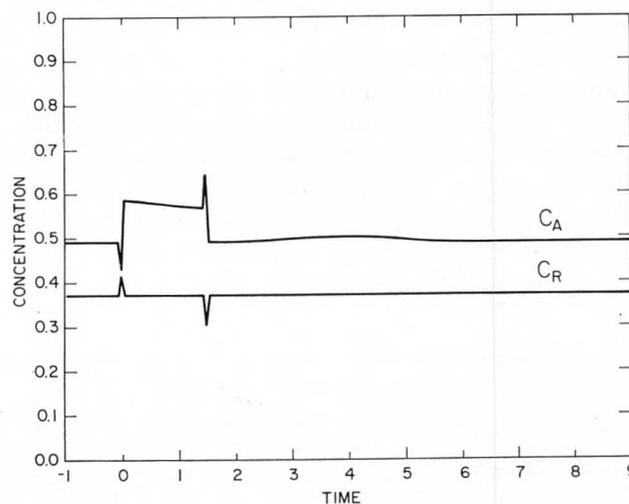


FIGURE 9

sible effect of the phenomenon is divergence of the system from the design steady state to one of the other steady states. This behavior is illustrated in Fig. 9. and Fig. 10 for the single exothermal reactor, with the  $2 \times 2$  control system sketched in Fig. 4. Following a temporary disturbance in feed concentration, the product concentrations  $c_A$  and  $c_R$  are returned to the desired values. However, the manipulations, in this case temperature and residence time, diverge to values at an alternate steady state.

This divergence would be difficult to detect in practice. First, because manipulations are not always monitored. Second, because even if the changes in manipulations are observed, they could well be due to a permanent change in a disturbance variable, for which the reset action has compensated by permanently changing (resetting) the

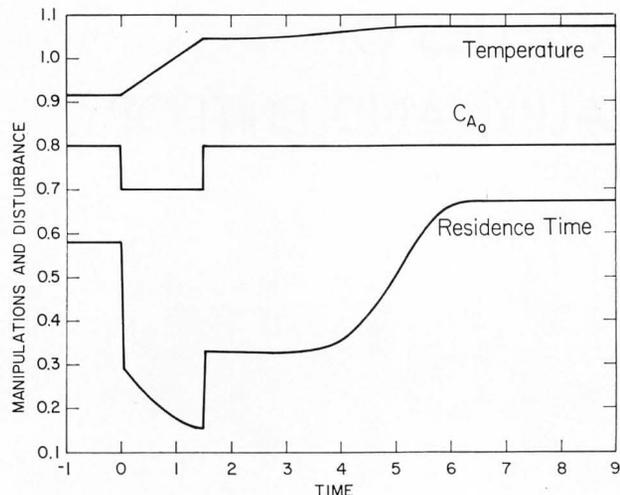


FIGURE 10

manipulations. Identification and monitoring of all possible process disturbances, which is not a practical idea, would be required to make this distinction with certainty.

The reactor control system is much less stable at the new steady state. In fact, it has been shown [8] that one of the loops is in positive feedback at this steady state. Its gain has the wrong sign. Therefore, even though the interactions stabilize the two loops together, the system is much more vulnerable than before to disturbances. Detection of the phenomenon in practice is more likely to occur indirectly, by observation of the undesirable sudden reduction in stability level. This phenomenon could explain the erratic behavior of some loops in chemical process control systems: they function well most of the time, but occasionally suffer a sudden reduction in stability level.

**Unconstrained Limit Cycles.** Another effect of input multiplicity, which has been demonstrated on the six-component reaction system studied by Rickard, is appearance of an unconstrained limit cycle. This is a periodic oscillation, of fixed amplitude and frequency, in which none of the variables ever reach constraints. This contrasts with a limit cycle in which, for example, at least one of the control valves is wide open or fully shut during some portion of the cycle. These constrained limit cycles usually occur because the control system is

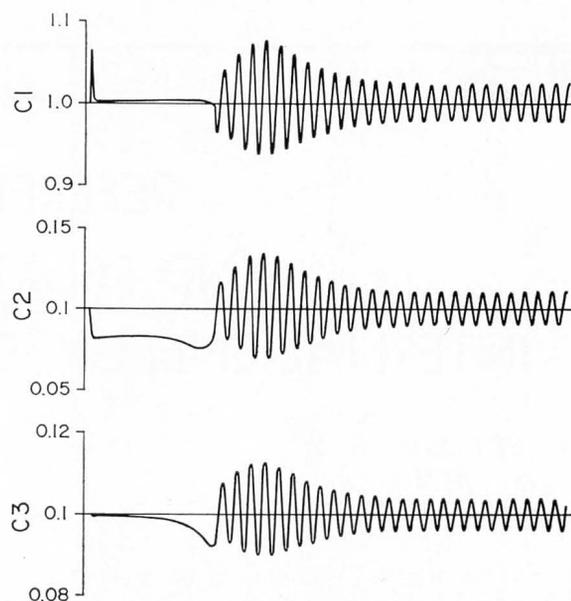


FIGURE 11. Outputs reach limit cycle around original steady state

unstable, but fortunately cannot exhibit the theoretical behavior of an ever-growing oscillation because of physical constraints on (typically) process flow rates.

An example of the unconstrained limit cycle behavior is illustrated in Figs. 11 and 12 [10]. The six-component reaction scheme discussed above is being conducted isothermally in a stirred reactor. The control system is using the feed concentration

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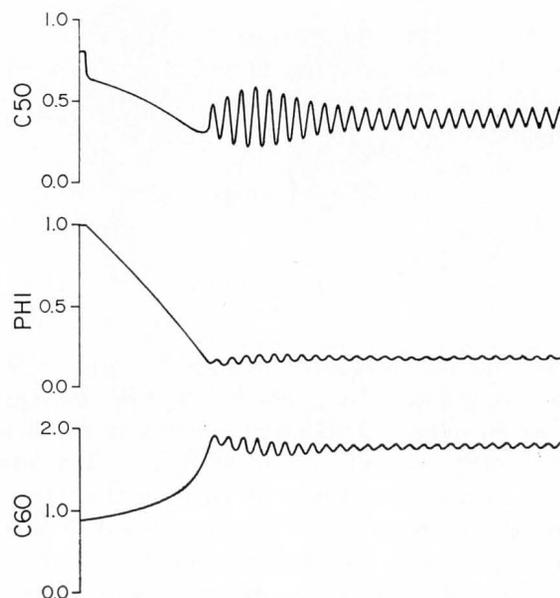
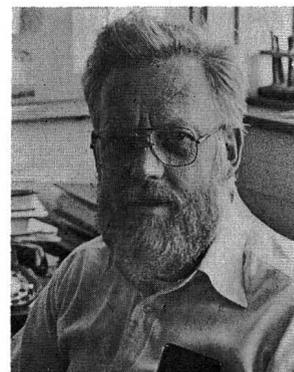


FIGURE 12. Inputs reach limit cycle around alternate steady state

# REFERENCE STATES AND RELATIVE VALUES OF INTERNAL ENERGY, ENTHALPY, AND ENTROPY

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**M**ANY PROBLEMS IN chemical engineering thermodynamics require for their solution the application of the balance equations for moles of various chemical species, (total) energy, and entropy. Fairly general forms of these equations, which are applicable to open, moving and deforming, and unsteady state systems, are

$$\frac{dN_j}{dt} = \sum_q w_q x_{q,j} + \sum_i \alpha_{ij} R_i \quad (1)$$

$$\frac{d}{dt} (U_t + K_t + \Phi_t) = Q + W_u + W_{exp} + \sum_q w_q (h_q + k_q + \phi_q) \quad (2)$$

$$\frac{dS_t}{dt} = S + S_G + \sum_q w_q S_q \quad (3)$$

Here, the energy and entropy transfer rates associated with heat transfer,  $Q$  and  $S$ , are related to the local heat flux vector  $\mathbf{q}$  and temperature  $T$  on the boundary  $\partial B$  of the system  $B$  by

$$Q = - \int_{\partial B} (\mathbf{n} \cdot \mathbf{q})$$

$$S = - \int_{\partial B} \frac{1}{T} (\mathbf{n} \cdot \mathbf{q})$$

The second law of thermodynamics requires that the entropy generation rate  $S_G$  shall be non-negative, and further, shall be non-negative for every subsystem into which  $B$  may be divided. The quantity  $\alpha_{ij}$  is the stoichiometric coefficient of the  $j^{th}$  chemical species in the  $i^{th}$  reaction,  $R_i$  is the rate of the  $i^{th}$  reaction in the system, and the summation on  $i$  in Eq. (1) is over a set of independent reactions [1]. The fact that all valid chemical re-

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action equations must be balanced is expressed by the conditions

$$\sum_j \alpha_{ij} \epsilon_{jk} = 0 \quad (4)$$

and this must be satisfied for all reactions ( $i$ ) and all elements ( $k$ );  $\epsilon_{jk}$  is the number of atoms of the  $k^{th}$  kind of element in one molecule (or meric or repeating unit) of the  $j^{th}$  chemical species. The quantity  $w_q$  is the molar flow rate of material at the  $q^{th}$  port of the system; it is positive if material enters the system at that port but negative if material leaves the system there. The mole fraction of the  $j^{th}$  chemical species in this stream is denoted by  $x_{q,j}$ . Finally,  $-W_u$  and  $-W_{exp}$  are the rates at which the system performs useful and expansion work on the surroundings, and  $K_t$  and  $\Phi_t$  denote kinetic and potential energy.

Eqs. (1-3) are not valid for systems which exchange matter with their surroundings by diffusion across a permeable boundary, but they are

easily generalized to include that case also. It can be shown that the results to be deduced here apply to these more general systems also, but in the interests of simplicity such systems will not be considered further here.

The quantities  $U_t$  and  $S_t$  which appear in Eqs. (2) and (3) are the *absolute* values of the internal energy and entropy of the system, respectively, and the quantities  $h_q$  and  $s_q$  which appear in these equations are the *absolute* values of the enthalpy and entropy of one mole of the  $q^{th}$  process stream, respectively. Thermodynamics provides means for calculating *changes* in  $U_t$ ,  $S_t$ ,  $h_q$ ,  $s_q$  when the system and the  $q^{th}$  process stream experience processes which change their states, but thermodynamics does not identify the states in which these quantities are zero. It is sometimes held that the third law of thermodynamics identifies such a state for the entropy but, within the context of classical thermodynamics at any rate, it is clear that this is not so: the third law, or rather the version of it usually called Nernst's heat theorem, asserts only that the entropy *changes* of certain kinds of systems undergoing certain kinds of isothermal processes approach zero as the temperatures of the processes approach absolute zero [2]. Hence, we do not know how to find the absolute values of  $U_t$ ,  $S_t$ ,  $h_q$ , and  $s_q$ .

However, we need to be able to assign numerical values to internal energy, entropy, etc. if we want to tabulate what effects changes of temperature, pressure, and composition have on them. Hence, reference states for internal energy, entropy, and enthalpy are chosen, and values of internal energy, entropy, and enthalpy relative to the reference states are tabulated. The most familiar example of this is the steam tables, but the utility of enthalpy-composition and related diagrams demonstrated in the well-known Hougen, Watson, and Ragatz book [3] make such diagrams nearly as familiar as the steam tables.

Let  $U_{trU}$  be the (absolute) internal energy of the matter of the system being considered when this matter is in the reference state for internal energy, and let  $S_{trS}$  be the (absolute) entropy of the matter of the system when this matter is in the reference state for entropy. Then the relative internal energy,  $U_t'$ , and relative entropy,  $S_t'$ , of the system are defined by

$$U_t' \equiv U_t - U_{trU} \quad (5a)$$

$$S_t' \equiv S_t - S_{trS} \quad (5b)$$

and the calculation of  $U_t'$  and  $S_t'$  involves only cal-

ulation of *changes* of internal energy and entropy. The reference quantities do not depend on the temperature and pressure of the system, though they do depend on its composition. Similarly, if we let  $h_{qRH}$  be the enthalpy of one mole of matter of the  $q^{th}$  process stream when this matter is in the reference state for enthalpy, then we can define a relative enthalpy

$$h_q' \equiv h_q - h_{qRH} \quad (5c)$$

as well as a relative entropy

$$s_q' \equiv s_q - s_{qRS} \quad (5d)$$

for the  $q^{th}$  process stream. It is necessary to place the subscript  $q$  on the reference state quantities  $h_{qRH}$  and  $s_{qRS}$  because these quantities depend on the composition of the  $q^{th}$  stream, and this is not in general the same as the composition of other process streams. However,  $h_{qRH}$  and  $s_{qRS}$  do not depend on the temperature and pressure of the  $q^{th}$  process stream.

If the relative properties  $U_t'$ ,  $S_t'$ ,  $h_q'$ ,  $s_q'$  are to be useful then they should obey the same balance equations as do the absolute properties  $U_t$ ,  $S_t$ ,  $h_q$ ,  $s_q$ ; that is, the relative properties should obey

$$\begin{aligned} & \frac{d}{dt} (U_t' + K_t + \Phi_t) \\ &= Q + W_u + W_{exp} + \sum_q w_q (h_q' + k_q + \phi_q) \end{aligned} \quad (6)$$

$$\frac{dS_t'}{dt} = S + S_G + \sum_q w_q s_q' \quad (7)$$

where  $Q$ ,  $W_u$ ,  $W_{exp}$ ,  $S$ , and  $S_G$  are the same quantities that appear in Eqs. (2) and (3). Clearly, if the relative properties satisfy these balance equations they then can be used (correctly) in the calculations of heat and work effects that occur so frequently in applied thermodynamics. I have been unable to find a recent discussion of the choices of reference states which will lead to Eqs. (6) and (7), and so provision of such discussion is the objective of this paper.

## REFERENCE STATE 1

### The Pure Chemical Compounds at Specified Conditions of T and p

Although it would be possible to choose reference states which are solutions we shall not do so here. Instead, we shall consider only reference states in which only pure substances, unmixed with other substances, are present, and present in states of aggregation that are at least metastable.

**If the relative properties . . . are to be useful then they should obey the same balance equations as do the absolute properties . . .**

To begin with, we choose the pure substances to be the pure compounds of which the system and the process streams are composed. The reference state for internal energy is assumed to involve in the most general case a different combination of temperature and pressure for each compound, and the temperature and pressure of the reference state for internal energy for a given compound are assumed to be different from the temperature and pressure of the reference state for entropy for that compound. If it is not possible to choose reference states in this very arbitrary way, we want to find that out.

It is easy to show that Eqs. (6) and (7) follow from Eqs. (2) and (3) and the definitions of Eqs. (5) if, and only if, the reference properties satisfy

$$\frac{dU_{trU}}{dt} - \sum_q w_q h_{qrH} = 0 \quad (8)$$

and

$$\frac{dS_{trS}}{dt} - \sum_q w_q s_{qrS} = 0 \quad (9)$$

These equations are general; they must be satisfied for every valid choice of reference states of  $U_t$ ,  $H_t$ , and  $S_t$ . It might be supposed at first that the time derivatives in these equations are zero, but such is not in general the case because, as pointed out above, the reference state quantities  $U_{trU}$  and  $S_{trS}$  depend on the composition of the system and this in general is time varying.

Consider the second of these equations first. Let  $s_{jrs}$  be the (absolute) molar entropy of the pure  $j^{th}$  compound when it is in the reference state for entropy. Then

$$S_{trS} = \sum_j N_j s_{jrs}$$

and

$$s_{qrS} = \sum_j x_{q,j} s_{jrs}$$

and from these we find that

$$\begin{aligned} \frac{dS_{trS}}{dt} - \sum_q w_q s_{qrS} &= \sum_j s_{jrs} \left( \frac{dN_j}{dt} - \sum_q w_q x_{q,j} \right) \\ &= \sum_j s_{jrs} \sum_i \alpha_{ij} R_i \\ &= \sum_i R_i \sum_j \alpha_{ij} s_{jrs} \end{aligned} \quad (10)$$

where Eq. (1) has been used. If *no chemical reactions occur*, Eq. (10) shows that Eq. (9) is satis-

fied by arbitrary choices of the entropies  $s_{jrs}$ , but if reactions occur, Eq. (10) shows that Eq. (9) will be satisfied if and only if we chose these entropies such that

$$\sum_j \alpha_{ij} s_{jrs} = 0 \quad (11)$$

for each and every independent reaction occurring. This shows that if chemical reactions occur, the conditions of temperature and pressure for the entropy reference states of the compounds of which the system is composed cannot be chosen arbitrarily, but must be chosen so that the entropies  $s_{jrs}$  satisfy a number of constraints equal to the number of independent reactions which occur.

Consider now Eq. (8). Let  $u_{jrU}$  ( $h_{jrH}$ ) be the (absolute) molar internal energy (enthalpy) of the pure  $j^{th}$  compound when it is in the reference state for internal energy (enthalpy). Then

$$U_{trU} = \sum_j N_j u_{jrU}$$

$$h_{qrH} = \sum_j x_{q,j} h_{jrH}$$

and so

$$\begin{aligned} \frac{dU_{trU}}{dt} - \sum_q w_q h_{qrH} &= \sum_j \left( u_{jrU} \frac{dN_j}{dt} - h_{jrH} \sum_q w_q x_{q,j} \right) \\ &= \sum_j (u_{jrU} - h_{jrH}) \frac{dN_j}{dt} \\ &\quad + \sum_i R_i \sum_j \alpha_{ij} h_{jrH} \end{aligned} \quad (12)$$

where again Eq. (1) has been used. This result shows that in the general case Eq. (8) will be satisfied if the reference states for internal energy are chosen so that

$$u_{jrU} = h_{jrH} \quad (13)$$

for all compounds present and

$$\sum_j \alpha_{ij} h_{jrH} = 0 \quad (14)$$

for all independent reactions occurring.

In summary of the case where the reference states involve the pure compounds, we state the following. If no reactions occur, the entropy reference states for the compounds can be chosen with complete arbitrariness, and the same is true of either the internal energy reference states or the enthalpy reference states for the compounds. Once one of these latter sets of states is chosen, however, the other set of states must be chosen so as to satisfy Eq. (13); if Eq. (13) is not satisfied, Eq. (6) will not be true for unsteady state situations in-

volving open systems even though no reactions occur. If chemical reactions occur, Eq. (13) must still be satisfied, and in addition the reference states for entropy and enthalpy must satisfy the constraints imposed by Eqs. (11) and (14). These constraints are inconvenient; Eq. (14) would force us to choose reference state temperatures for the enthalpies of gases to be different for different gases, for example. Hence, we consider a reference state which is not subject to such constraints.

## REFERENCE STATE 2

### The Pure Elements at Specified Condition of T and p

We assume now that material in a reference state is present as the pure *elements*, unmixed with other elements or compounds, in stable or metastable states of aggregation and (in general) at different conditions of temperatures and pressure for different elements.

Let  $S_{krS}^E$  be the (absolute) molar entropy of the  $k^{\text{th}}$  kind of element in the reference state for entropy. Then

$$S_{trS} = \sum_j \sum_k N_j \epsilon_{jk} S_{krS}^E$$

and

$$S_{qrS} = \sum_j \sum_k x_{q,j} \epsilon_{jk} S_{krS}^E$$

From these, we get

$$\begin{aligned} \frac{dS_{trS}}{dt} - \sum_q w_q S_{qrS} &= \sum_j \sum_k \epsilon_{jk} S_{krS}^E \left( \frac{dN_j}{dt} - \sum_q w_q x_{q,j} \right) \\ &= \sum_i \sum_j R_i S_{krS}^E \sum_j \alpha_{ij} \epsilon_{jk} = 0 \end{aligned}$$

because of Eq. (4). Hence, with this choice of reference state for entropy, Eq. (9) will always be satisfied, even for systems in which chemical reactions occur.

Let  $u_{krU}^E$  ( $h_{krH}^E$ ) be the (absolute) molar internal energy (enthalpy) of the  $k^{\text{th}}$  kind of element in the reference state for internal energy (enthalpy). Then

$$U_{trU} = \sum_j \sum_k N_j \epsilon_{jk} u_{krU}^E$$

and

$$h_{qrH} = \sum_j \sum_k x_{q,j} \epsilon_{jk} h_{krH}^E$$

From these, we find that Eq. (8) will be satisfied for all cases if we chose reference states for internal energy and enthalpy such that

$$u_{krU}^E = h_{krH}^E \quad (15)$$

and the fact that chemical reactions occur imposes no constraints of the types imposed by Eqs. (11)

and (14). We see, therefore, that the temperature and pressure of the reference state for entropy of a given element can be chosen with complete arbitrariness, as can the temperature and pressure of the reference state for internal energy or enthalpy of a given element.

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... this ... leads to a problem  
that cannot be solved: we cannot know  
how to adjust the heat transfer rate to the gas so  
that its absolute total internal energy remains  
constant as its mass changes.

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### RELATION BETWEEN REFERENCE STATES FOR INTERNAL ENERGY AND ENTHALPY

The foregoing analysis shows that if Eqs. (6) and (7) are to be correct in all circumstances, then the temperatures and pressures of any pure substance (compound or element) in the reference states for internal energy and enthalpy must be such that

$$u_{rU} = h_{rH} \quad (16)$$

where we have dropped subscripts and superscripts identifying the particular element or compound considered. If the mole numbers  $N_j$  are independent of time, Eq. (6) will be valid even if reference states are not chosen so that Eq. (16) is valid. That means that it is not necessary to choose reference states so that this equation is true if we are dealing with steady state open systems (in which reactions may be occurring) or closed systems in which no reactions are occurring. In all other cases, however, Eq. (16) must be satisfied if Eq. (6) is to hold.

The internal energy and enthalpy in the reference state for internal energy must satisfy the usual relation.

$$h_{rU} = u_{rU} + p_{rU} v_{rU} \quad (17)$$

and combination of this with Eq. (16) shows that

$$h_{rH} - h_{rU} = -p_{rU} v_{rU} \quad (18)$$

This equation tells us how we must choose the reference state for enthalpy if the reference state for internal energy is chosen. In the 1967 ASME steam tables, for example, the reference states for entropy and internal energy are chosen to be liquid water at the triple point (273.16K, 611.2N/m<sup>2</sup>), and the p-V product for liquid water at this condition is 11.0 J/kmol. It follows from Eq. (18) that the reference state for enthalpy can be any state for which the molar enthalpy of water is less than

the molar enthalpy of liquid water at the triple point by 11.0 J/kmol. This difference could be achieved by lowering the temperature of liquid water by 0.0026K while keeping pressure constant at 611.2 N/m<sup>2</sup>, for example. Liquid water at this condition (metastable, by the way) has an enthalpy which is less than the enthalpy of liquid water at the triple point by 11.0 J/kmol. However, other states could also serve as the reference state.

One does not have to make an actual choice of reference state for enthalpy once the reference state for internal energy is decided upon. This is so because when these reference states satisfy Eq. (16) for every compound or element, then the relation between *relative* enthalpy and internal energy is the same as the relation between *absolute* enthalpy and internal energy. Thus, if the reference states involve the pure elements, we have for the system

$$U_t = U_t' + \sum_j \sum_k N_{jk} \epsilon_{jk} u_{krU}^E$$

and

$$H_t = H_t' + \sum_j \sum_k N_{jk} \epsilon_{jk} h_{krH}^E$$

so

$$H_t - U_t = (H_t' - U_t') + \sum_j \sum_k N_{jk} \epsilon_{jk} (h_{krH}^E - u_{krU}^E) = H_t' - U_t' \quad (19)$$

if Eq. (16) is satisfied. Similarly, one can show that  $h_q - u_q = h_q' - u_q'$  if Eq. (16) is satisfied. For equilibrium systems a system pressure can be defined and  $H_t - U_t = H_t' - U_t' = pV$  so the relative value of enthalpy is fixed once the relative value of internal energy is stated, provided that Eq. (16) is satisfied by the choice of reference states.

## AN APPLICATION

Problem 5.11 in the book of Modell and Reid [4] provides an interesting application of the foregoing ideas. In this problem the total internal energy of a gas (helium) in a tank is to be held constant as gas flows out of the tank, and this is to be done by addition of heat to the gas in the tank at the proper rate; one is to calculate how the pressure and temperature of the gas vary with the amount of gas remaining in the tank. Since no chemical reactions occur, reference state 1 may be used. Indeed, reference states 1 and 2 are identical in this problem, but they would not be if the gas involved was a chemical compound composed of two or more elements.

The system to which mole and energy balances are to be applied is the gas in the tank, and the simplifying assumption that the gas has a spatially

uniform state at any time is made. Eqs. (5a) and (16) then provide, for an interval of time  $t$  to  $t + dt$ ,

$$dU_t = dU_t' + u_{rU} dN = dU_t' + h_{rH} dN \quad (20)$$

and in addition we have

$$H_t - U_t = H_t' - U_t' = pV \quad (21)$$

when  $u_{rU} = h_{rH}$ . Finally, the energy balance yields

$$dU_t' = dQ_t + h'dN \quad (22)$$

when mechanical energy terms in the equation are assumed to cancel one another. No expansion work term appears in this equation since the system volume is constant and no useful work term appears because we assume energy is added or removed by heat transfer rather than by performance of useful work.

If we interpret the statement of the problem in the Modell and Reid book to mean that *absolute* internal energy (total) is constant, then  $dU_t = 0$  and from Eqs. (20-22) we obtain after some manipulation

$$-hdN = Ndh' - Vdp (= dQ_t) \quad (23)$$

where the volume,  $V$ , of the system is constant. Since  $N$ ,  $h$ , and  $h'$  are functions of  $T$ ,  $p$ , and  $V$  this is an ordinary differential equation in the two state variables  $T$  and  $p$ . Certainly, we can write equations for the functional dependence of  $N$  and  $h'$  on these quantities for any given gas, once a choice of reference state has been made, but we cannot do the same for the absolute molar enthalpy,  $h$ . Hence, this interpretation of the problem statement leads to a problem that cannot be solved: we cannot know how to adjust the heat transfer rate to the gas so that its absolute total internal energy remains constant as its mass changes.

On the other hand, if we interpret the statement of the problem to mean that the relative internal energy (total) is constant, then  $dU_t' = 0$  and from Eqs. (20-22) we get

$$-h'dN = Ndh' - Vdp (= dQ_t) \quad (24)$$

Every term in this equation may be evaluated. If, for example, we assume that helium is a perfect gas with molar heat capacity  $c_p$  independent of temperature, then

$$h' = c_p(T - T_{rH}) \quad (25)$$

$$N = \frac{pV}{R_g T} \quad (26)$$

and Eq. (16) requires that the temperatures in the

reference states for internal energy and enthalpy satisfy

$$\gamma T_{rH} = T_{rU} \quad (27)$$

where  $\gamma \equiv c_p/c_v$ . One notes in passing that reference state temperatures for internal energy and enthalpy are substantially different in the case of a gas; as we noted, these temperatures were practically the same for a condensed phase because the pressure-volume product is usually very small for such.

Substitution of Eqs. (25-27) into Eq. (24) yields the differential equation

$$\frac{dp}{p} = \frac{dT}{T} + \frac{dT}{T_{rU} - T} \quad (28)$$

and this may be integrated subject to an appropriate initial condition to yield the relation between  $T$  and  $p$  that must be satisfied if  $U_t'$  is to be constant when  $N$  varies. The result contains the reference temperature  $T_{rU}$ , and this is to be expected, since if we change  $T_{rU}$ , we change the relative internal energy of the system when it is in a given state.  $\square$

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#### NOTATION

$c_p, c_v$	Heat capacities at constant pressure and volume, respectively, per mole
$H_t$	Enthalpy, total
$h$	Enthalpy, per mole
$K_t$	Kinetic energy, total
$k$	Kinetic energy, per mole
$N$	Number of moles in system
$n$	Unit outer normal vector to boundary $\partial B$ of system $B$
$p$	Pressure
$Q$	Rate of heat transfer into system
$Q_t$	Amount of heat transferred, total
$q$	Heat flux vector

#### REQUEST FOR FALL ISSUE PAPERS

Each year CHEMICAL ENGINEERING EDUCATION publishes a special fall issue devoted to graduate education. This issue consists of articles on graduate courses and research written by professors at various universities, and of announcements placed by ChE departments describing their graduate programs. Anyone interested in contributing to the editorial content of the fall 1983 issue should write to the editor, indicating the subject of the paper and the tentative date it can be submitted. Deadline is June 15th.

$R$	Rate of reaction
$R_g$	Gas constant
$S$	Rate of entropy transfer into system
$S_G$	Rate of entropy generation in system
$S_t$	Entropy, total
$s$	Entropy, per mole
$T$	Absolute temperature
$t$	Time
$U_t$	Internal energy, total
$u$	Internal energy, per mole
$V$	Volume
$v$	Volume, per mole
$W_t$	Work, total
$-W_{exp}$	Rate at which system does expansion work on surroundings
$-W_u$	Rate at which system does useful (shaft, electrical, etc.) work on surroundings
$w$	Molar flow rate
$x$	Mole fraction
$\alpha_{ij}$	Stoichiometric coefficient of $j^{th}$ compound in $i^{th}$ reaction
$\gamma$	Ratio of heat capacities
$\epsilon_{jk}$	Number of atoms of $k^{th}$ element in one molecule of $j^{th}$ compound
$\Phi_t$	Potential energy, total
$\phi$	Potential energy, per mole

#### Superscripts

$E$	Denotes property of a pure element
$'$	Denotes a relative property

#### Subscripts

$G$	Generation
$i$	Denotes $i^{th}$ reaction
$j$	Denotes $j^{th}$ chemical compound
$k$	Denotes $k^{th}$ element
$q$	Denotes $q^{th}$ process stream
$t$	Total
$rH, rS, rU$	Denote reference states for enthalpy, entropy, and internal energy

# LABORATORY EXPERIMENT

## FOR THE TRANSIENT RESPONSE OF A STIRRED VESSEL\*

R. D. NOBLE<sup>1</sup>, R. G. JACQUOT<sup>2</sup>, AND  
L. B. BALDWIN<sup>3</sup>

**A** LABORATORY EXPERIMENT has been developed to measure the transient response of a stirred vessel. The experimental apparatus is simple in construction, inexpensive to purchase, and gives good quality data which demonstrate the phenomenon being tested. The apparatus can be used for two different experiments which demonstrate transient behavior, thus further reducing the cost per experiment. Both experiments use salt dilution as the method of demonstration.

In one experiment, the vessel is initially charged with a known volume of water and known weight of salt. A measured inlet flow of water is started and the students determine salt concentration vs. time using a conductivity meter. They then

\*Paper published in Proceedings of Frontiers in Education Conference, Rapid City, SD (1981).

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**Richard D. Noble** received his B.E. degree in 1968 and M.E. degree in 1969 from Stevens Institute of Technology. In 1976, he received his PhD degree from the University of California, Davis. His current research interests include facilitated transport in liquid membranes, transient heat transfer, and problem solving skills. (L)

**Raymond G. Jacquot** is currently Professor of Electrical Engineering at the University of Wyoming where he served in the various academic ranks and served as Electrical Engineering Department Head for two and one half years. Dr. Jacquot's education includes B.S. and M.S. degrees in Mechanical Engineering from the University of Wyoming and the PhD in M.E. from Purdue. His professional interests are in dynamic systems and control and he is the author of **Modern Digital Control Systems**. He is a member of ASEE, IEEE, ASME and Vice Chairman for Regional Activities for the CoEd division of ASEE. (C)

**Leonard B. Baldwin** is currently Professor of Civil Engineering at the University of Wyoming. He holds B.S. (Physics) and M.S. (Civil

Engineering-Mechanics) degrees from Michigan State and the PhD in Civil Engineering from Stanford. He has held academic appointments at the University of Idaho, Michigan State, Tufts, Stanford and Michigan Technological University. His professional interests are in hydraulics of pipelines, hydrology and fluid mechanics. He is currently authoring text material in statics and dynamics with accompanying audio-tutorial tapes and slides. He is a member of ASEE. (R)

compare their experimental results with theoretical predictions. This experiment demonstrates the effect of volume change in the vessel on transient response.

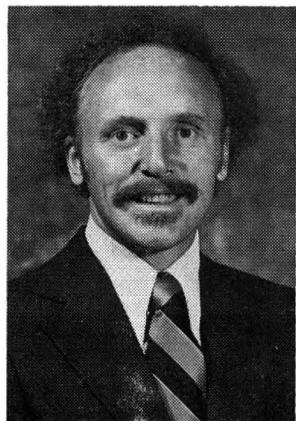
The second experiment is set up in the same fashion as the first except an outlet flow from the vessel is used so the tank volume remains constant. Students measure the salt concentration in the outlet as a function of time and compare this to theoretical predictions. This experiment demonstrates the effect of inflow and outflow on transient response.

The quality of the data obtained is very good and allows the student to observe the phenomenon and see how the theory is actually applied. Students are also asked to comment on sources of error in the experiment.

### THEORY

A macroscopic mass balance for a given species (component) in a system is

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$$\frac{d}{dt}(CV) + Q_o C_o - Q_i C_i - R = 0 \quad (1)$$

where:  $V$  = system volume  
 $C$  = species concentration  
 $Q$  = volumetric flowrate  
 $R$  = generation term  
 $i$  = inlet  
 $o$  = outlet

The systems to be studied have no chemical reactions taking place ( $R=0$ ) and are contained in a well-mixed vessel. Therefore, the outlet concentration  $C_o$  and the system concentration  $C$  are assumed equal. Eq. (1) will be applied to the salt contained in the vessel for each case. Also, the inlet stream contains pure water so  $C_i = 0$ .

For the first experiment, the outlet flowrate  $Q_o$  is zero and Eq. (1) becomes

$$\frac{d}{dt}(CV) = 0 \quad (2)$$

The solution for this equation is

$$C = \frac{C_1 V_1}{V_1 + Qt} \quad (3)$$

where the subscript 1 refers to the initial state of the system.

For the second experiment, the volume in the vessel remains constant and the outlet has a constant flowrate. Eq. (1) becomes

$$V \frac{dC}{dt} + Q_o C = 0 \quad (4)$$

The solution to Eq. (4) becomes

$$C = C_1 \exp(-Q_o t/V) \quad (5)$$

Eqs. (3) and (5) are the theoretical predictions against which the experimental results will be compared.

#### EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the experimental apparatus is shown in Fig. 1. A cylindrical vessel (nominal size: 10 gallons) has an outlet at the bottom with a valve to adjust or shut off flow. A water line with a valve for flow adjustment serves as the inlet. The water line should have a flexible section at the end so it can be removed from the vessel when necessary. A stirrer is mounted so that the contents of the vessel are well-mixed at all times. To further reduce costs, students can provide the mixing power. Not shown in the schematic is an electrical conductivity meter which is used to measure salt

The apparatus can be used for two different experiments which demonstrate transient behavior, thus further reducing the cost per experiment.

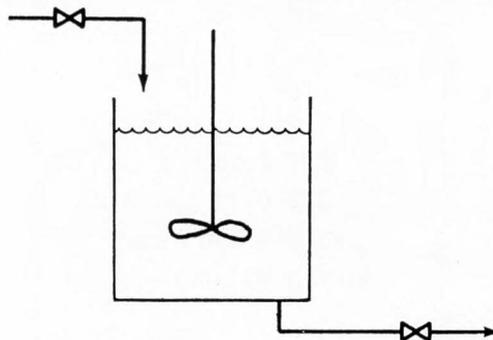


FIGURE 1. Schematic of experimental apparatus

concentration in liquid samples and a stop watch.

To perform the experiment with the outlet valve closed (amount of salt in system is constant and volume changes with time), a measured mass of salt and volume of water is added to the tank and well stirred. The initial concentration of salt is measured with the conductivity meter. It is important that all the salt dissolve into solution. The inlet line is turned on and the flowrate of water measured. This is done while the line is *not* discharging to the tank. At  $t=0$ , the inlet line is placed into the tank and the stop watch started. Samples are withdrawn periodically from the tank and the salt concentration measured. These experimental values are then compared to theory using Eq. 3. Fig. 2 shows some experimental and theoretical results for this experiment.

To perform the experiment with the outlet valve open (volume remains constant and amount of salt decreases with time), the tank is initially filled with water and the inlet flow rate is adjusted until the volume remains constant in the tank with the outlet valve open. The outlet valve is closed and the inlet line removed from the tank. A measured quantity of salt is then mixed into the system and an initial conductivity reading taken. At  $t=0$ , the inlet line is replaced in the tank, the outlet is reopened, and the stop watch started. Samples are taken periodically and the salt concentration is measured. Eq. 5 is then used to compare the experimental results with theory. Fig. 3 shows a comparison of theoretical and experimental results.

For both experiments, the student is given the macroscopic mass balance and asked to derive the theoretical result and compare it to the experi-

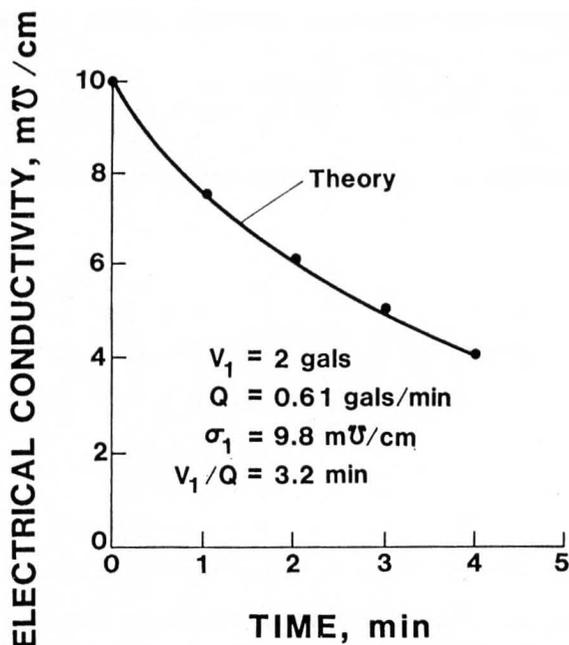


FIGURE 2. Results for closed outlet experiment

mental result. Also, the student is asked to comment on any sources of error in the experiment.

### RESULTS AND CONCLUSIONS

As seen by Figs. 2 and 3, the comparison between experimental and theoretical results is very good. The data obtained is very reproducible and consistent with theory. This reinforces the validity and the limitations of the theory for the student and removes it from a strictly textbook context.

The experimental apparatus is simple in design and inexpensive. Yet, it provides the opportunity to perform two different experiments and thereby, further reduce storage space and cost per experiment.

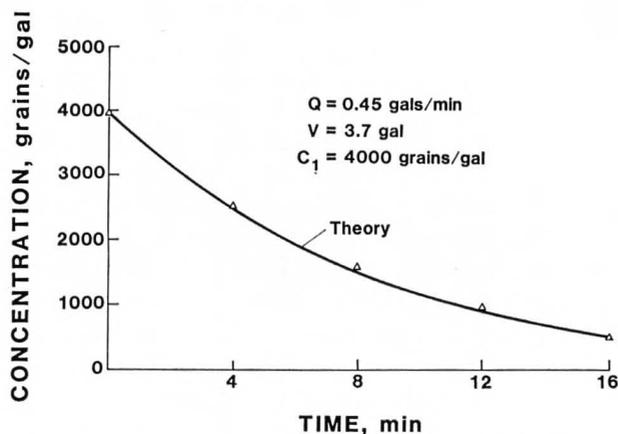


FIGURE 3. Results for constant volume experiment

The experimental procedure is also simple and allows the student to focus attention on the physical phenomenon taking place and not get immersed in the procedural detail. Students can perform multiple experiments since the procedure is simple and short in time. This also reinforces the validity of their results. Multiple tests could also be used to instruct students in data analysis (mean and variance, for example).

It is also quite simple to set up multiple experimental apparatuses so that many different groups of students could perform the experiments simultaneously. After performance, the apparatuses could also be removed and stored so that the space was available for other use.

In conclusion, the following points can be made.

- An experimental apparatus has been described which demonstrates the transient response of a stirred vessel. The apparatus is flexible in application and can be used for two different experiments.
- The experimental results are very good and consistent with theory.
- The apparatus is inexpensive and simple to operate. □

## ChE letters

### SUPPLEMENTS FOR THERMO FILMS

Sir:

For some years I have used the films by Noel de Nevers entitled *Phase Behavior, Parts I and II* in my courses in thermodynamics. Using high-pressure visualization equipment and time-lapse photography, Prof. de Nevers shows examples of phase transitions in both pure and multicomponent systems. The films demonstrate skillfully those aspects of fluid-phase behavior that are frequently discussed by chemical engineers.

Because so much information is presented, however, I have found that students often miss some of the subtleties. In most sequences viewers must watch a moving phase boundary along with temperature and pressure gauges, and then correlate their observations with Prof. De Nevers' commentary. For the beginning student, this can be quite difficult.

To help solve this problem, I have prepared brief summaries of the sequences. These may be discussed with students both prior to and after showing the films and also used as a basis for more lengthy study of phase behavior. I believe that the films, together with such discussions, have great pedagogical value in thermodynamics, and I would be pleased to make these write-ups available to others on request. The two films currently have a rental cost of \$14.50 each and may be obtained from the University of Utah, Instructional Media Services, 207 Milton Bennion Hall, Salt Lake City, UT 84112.

Kenneth R. Jolls  
Iowa State University

## *In Memoriam*

# *Joseph J. Martin*



Joseph J. Martin, professor of chemical engineering at the University of Michigan and associate director of its Institute of Science and Technology, died on December 13, 1982, just ten days before his 66th birthday.

Joe had been a member of the University of Michigan faculty since 1947, and in recognition of his many contributions and excellence in teaching was to have received the 1982 Outstanding Teacher of the Year Award from its College of Engineering. The award was presented to him posthumously, and was only the latest addition to a long list of honors, awards, and prizes given to Joe over the past 40 years for his work and contributions, primarily in the field of thermodynamics.

A native of Anita, Iowa, Joe received his BS from Iowa State University in 1939, his MS from the University of Rochester in 1944, and his DSc from Carnegie Mellon University in 1949. He was acting director of the Institute of Science and Technology at the University of Michigan from 1978 to 1981, founder and first chairman of the Association for Cooperation in Engineering, and former president of AIChE, ASEE, and the Engineers Joint Council.

It was through the Association for Cooperation in Engineering that Joe's goal of a unified voice for engineering came to fruition. A visible result of his efforts is this journal, *CEE*, which came into being during Joe's tenure in ASEE. He also served on the Engineers Council for Professional Development and was chairman of the Education and Accreditation Committee of the AIChE at the time of his death. He was the author of two books and more than 100 technical papers.

Joe's love and appreciation for thermodynamics was unwavering and he and his students devoted over four decades to obtaining precise thermodynamic data of substances so as to provide the testing ground for the "Holy Grail" of thermodynamics—a General Equation of State. Nearly a third of his more than 100 publications were re-

lated to this effort. The remaining two-thirds may have been overshadowed by his achievements in thermodynamics, but in their own right were significant landmarks in other disciplines. For example, recognition of Joe's pioneering work in radiation chemistry led to his election as chairman of the Division of Nuclear Chemistry and Technology of the American Chemical Society and also to the chairmanship of the Nuclear Engineering Division of the AIChE.

Joe's attitude toward his profession and his motivation for participation in society activities is best expressed in his own words:

We have an unusual collection of talent in our memberships, drawn from industry, government, and education, and are capable of directing it in a relevant manner for the best interests of the individual, the specific group, and the nation as a whole. Thus, a profession does not exist in a vacuum—but derives its meaning, value and goals through both its responsiveness to needs of society and its influence on the direction of society. Being an engineer carries with it a serious responsibility which must be met in a considered, thoughtful manner by the engineers who are developing the new technologies if these advances are to play a positive role in our society.

Joe's energies and activities were not, however, restricted to his scientific field. He was a longtime member of the Ann Arbor Housing Commission, having served from 1968 to 1978, and was an avid tennis player. A boyhood interest in the game led to his lifelong love of the sport and he played competitively for over 35 years. He won, among other titles, the "Ann Arbor Men's Singles: Over 40" title in 1978, and continued to play even after surgery replaced his right hip joint in 1981.

Survivors include his wife, Merrilyn (Terry); two daughters, Judy Lee Martin and Jacque Martin Downs; two sons, Joseph J. B. Martin and Jon T. F. Martin; two sisters, and two grandchildren. □

# THE INFUSION OF SOCIO-HUMANISTIC CONCEPTS INTO ENGINEERING COURSES

*via Horizontal Integration of Subject Matter\**

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**D**URING THE PAST DECADE, many universities have been critically reappraising the effectiveness of some of their traditional elective courses in view of the rapidly changing needs of professional education in a wide variety of fields including science, engineering, business administration, journalism, law and medicine. No longer is it possible for professionals in any of these fields to function in a comfortable milieu designed and limited largely by its practitioners. A number of significant trends are discernible in the interaction among the professions, society, and higher education. Irrespective of the particular professional field, the same questions keep recurring. Prominent among these are the sensitivity of the professions to social needs, the concept of professionalism and professional competence, the problem of licensure of professionals and of the maintenance and upgrading of competence, the opening of licensing boards to lay people, the emphasis on ethics, values, motivations and the need for a broader, more humanistic and humane view on the part of decision makers and their advisors. As a result, an urgent call is being heard from many sectors for a "new breed" of professional whose training and values reach beyond the cost-efficiency considerations to include an assessment of the political, social, and human dimensions of the problem at hand.

\*Paper presented at Annual Meeting of the AIChE, Chicago (November 18, 1980).



**Charles Huckaba** heads his own consulting firm in New York. He has a varied background in engineering, medicine and applied mathematics involving academic/industrial/government affiliations. The work described in this paper was carried out during his tenure as Director of Engineering Program Development at the Cooper Union. Dr. Huckaba received academic training in chemical engineering at Vanderbilt, M.I.T. and the University of Cincinnati and is a Fellow in the American Institute of Chemical Engineers. He is also a member of ASEE.

**Anne Griffin** is Assistant Professor of Political Science at The Cooper Union. A member of the Humanities faculty, she has taught courses on public policy, technology and society, and urban politics, and has played an active role in the development of curricula for the School of Engineering. Dr. Griffin has also participated in projects dealing with the interfaces between technology and politics. She holds a BA from Wellesley College and an MA and PhD from New York University. (Not pictured)

## TREND TOWARD THE HUMANITIES

Over the past quarter century, engineering education has been evolving toward a more "liberal" format, with an increasing emphasis upon the humanities and social sciences to complement the technical content of the curriculum. In 1951, the Engineers Council for Professional Development mandated that to meet minimum accreditation requirements, all undergraduate engineering curricula must contain 20% non-technical (humanities, social sciences) courses. Even though this move constituted a significant break away from the almost total preoccupation with the de-

velopment of technical expertise, the effect (although salutary) has been of limited impact. Examination of the transcripts of recent engineering graduates reveals little perceptible focus on, or coordination among, the non-technical courses elected; one strongly suspects that such criteria as convenience of scheduling, word-of-mouth reports on amount of work required, etc., were the primary factors influencing the choice of those courses. Whereas the resulting potpourri, no doubt, induced some alternate viewpoints for the students, the result in most cases falls far short of the intended impact.

Dr. Simon Ramo\*, an engineer who was formerly an advisor to the White House, recently argued

Engineers must spend as much time learning about and dealing with society as they do in applying science and technology to society and its problems. The present veneer of humanities and social sciences in university engineering curricula is quite inadequate for this purpose.

\*Ramo, Simon. 75th Anniversary Convocation, National Bureau of Standards (1976).

... an urgent call is being heard from many sectors for a "new breed" of professional whose training and values reach beyond the cost-efficiency considerations to include an assessment of the political, social, and human dimensions of the problem at hand.

Certainly we can agree that the "humanizing" of professional education requires more than merely encouraging students to read a few more humanistic texts in the hope that a stronger awareness of the human implications of their activities will occur by magic contagion.

#### PROPOSED APPROACH

In an attempt to address this problem, in 1976 a group of educators from various disciplines at the Cooper Union (originally under the initiative of the Engineering School) launched a curricular reform study with the firm intent to compose a genuinely interdisciplinary (not just mutidisciplinary) approach to engineering education. One of the significant results of this study was a proposal

TABLE 1  
Social Aspects of the Technical Decision Process

*Technological advances are increasingly shaping contemporary society and culture. Professionals in many fields recognize that it is no longer possible to function in traditional contexts. This course will examine the social, ethical, and humanistic dimensions of currently critical problem areas, especially natural resource limitations, energy alternatives, and environmental issues, wherein social and human impact are equal in importance to technical/economic criteria. Course format will encourage effective horizontal integration of guiding concepts from the humanities and technical disciplines.*

#### TOPICS

- Science, engineering and technology.
  - Their place in the spectrum of human knowledge.
  - Interrelationships among them.
- Case studies in engineering ethics. (See Table 2)
- The current dialogue between technology and social philosophy.
- Independent projects involving social and technical aspects. (See Table 3)
- Setting standards: Values, valuation and applications.
- Summary and conclusions.

#### TEXTS

- Baum, Robert J. and Albert Flores, Ethical Problems in Engineering. The Center for Human Dimensions, Rensselaer Polytechnic Institute, Troy, NY (1978).

- Florman, Samuel C., The Existential Pleasures of Engineering, St. Martins, NY (1976).
- Kuhn, Thomas S., The Structure of Scientific Revolutions, 2nd ed., University of Chicago Press, Chicago (1970).

#### ADDITIONAL READING REFERENCES

- Dubos, René, So Human an Animal, Scribner, NY (1968). pp. 181-242.
- Ellul, Jacques, The Technological Society, Knopf, NY (1964). pp 1-22; 65-79.
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- Roszak, Theodore, Person/Planet—The Creative Disintegration of Industrial Society, Anchor Press/Doubleday (1979). pp xix-xxx; 27-39; 132-137; 306-321.
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to effect a horizontal integration (topical and methodological) of humanities/social sciences subject matter with the engineering/design content of the curriculum. This would be accomplished in a team teaching format, involving both humanities and engineering faculty members concerned with the human and social implications of supposedly neutral technologies and methodologies.

### THE EXPERIMENTAL COURSE

The initial attempt to implement this concept involved a course entitled "Social Aspects of the Technical Decision Process," which was team taught by the authors.

Course content was built around an integrated set of topics and related specific problem formulations cutting across disciplinary boundaries, such as alternative energy, ecology, urban planning, etc., which represent traditional engineering concerns but have built-in social and historical dimensions. A guiding question was whether the latter are mere additional concerns which one may or may not deal with depending upon one's sense of involvement, or whether such concerns might not affect the very problem formulations themselves.

Table 1 indicates the course content. The central concern of the "horizontally integrated" topical core, as exemplified in this initial course, was the relation between professional competence and (supposedly extraneous) ethics and social impact,

**TABLE 2**

#### Ethics Cases Considered from Baum and Flores

*A case was chosen by each student for oral presentation and critique to the class. The cases considered in this manner were:*

- **Engineering Ethics: A Blend of the Ideal and the Practical** (p 30)
- **Ethics, Engineering, and Publicity** (p 91)
- **False Statements in Advertising** (p 102)
- **Conflict of Interest—Related Work for Two Parties** (p 115)
- **Liability and the Engineer—Responsibility to Former Employers** (p 145)
- **Misuse of Confidential Information** (p 152)
- **An Anatomy of Whistle Blowing** (p 168)
- **The Case of the Three Engineers vs. BART** (p 227)
- **Carl W. Houston and Stone and Webster** (p 262)
- **The Life and Times of Lawrence Tate** (p 288)
- **A Research Pirate in Action: The Case of Dr. Aries** (p 290)
- **Old Secrets in a New Job** (p 292)
- **Reactor Safety: Independence of Rasmussen Study Doubted** (p 301)

**TABLE 3**  
**Term Papers**

*Each student in consultation with the course instructors prepared a report on a contemporary topic involving both technical and social impact factors. Each topic was first presented orally to the class to elicit suggestions and criticisms and then a written report was prepared. Topics of the papers were:*

- **Recombinant DNA—Technology and Social Aspects**
- **Dilemmas of the Technological Polity**
- **Being There (Jerzy Kosinsky)—The Plight of the Self-Made Man**
- **The Supersonic Transport—Should it Continue?**
- **Microwaves**
- **Space Colonization**
- **Fluoridation—Pros and Cons**
- **Television and Society**
- **Nuclear Wastes**
- **Technology vs. the Environment, A Case Study: Insecticides**
- **Sperm Bank/Artificial Insemination (AID) Technology: The Technique and its Social Implications**
- **Government Interventions in the Business of IT&T**

including an examination of the basic concept of professionalism itself. To prevent these considerations from appearing to be nothing more than academic moralizing, this material was couched in the context of presently critical technological problem areas such as those listed in Tables 2 and 3.

For example, in the initial layout of a new processing plant or in the preliminary design of an electrical power distribution system, students can be led to recognize the necessity of considering, in the early stages of planning, the impact upon both the social and natural environments in addition to the usual technical and economic criteria. Failure to do so may lead not only to costly delays or expensive modifications of the operating system but above all, to unacceptable human consequences. In considering a series of examples of this type, the students begin to recognize that it is expeditious to consider the technical-social system as the unified entity which it really is, rather than artificially subdividing it into components which, in the final design, may not mesh in a compatible manner. In short, the students are led to realize that the understanding of social/political phenomena is as necessary as the acquiring of technical expertise.

#### ACKNOWLEDGMENT

The work reported in this paper was supported by a grant from the National Endowment for the Humanities. □

## **ChE** book reviews

### **CHEMICALS IN THE ENVIRONMENT: DISTRIBUTION-TRANSPORT-FATE- ANALYSIS**

*By W. Brock Neely*

*Marcel Decker, Inc., New York, 1980. 245 Pages*

**Reviewed by Alfred J. Engel**  
**Pennsylvania State University**

The author of this book, Dr. W. Brock Neely, is a biochemist by training and now works in the Environmental Research Laboratory of the Dow Chemical Company. It seems that the book is the indirect result of his self-education in the area of mathematical modeling of environmental phenomena. Six of the book's seven chapters, as well as most of the appendix, deal with a variety of models, from the compartmental approach to eco-systems, to dispersion methods in air and water pollution. Unfortunately, none of this material is of sufficient depth or comprehensiveness to allow the untrained reader to gain much expertise in the use of the models. On the other hand, the experienced reader will find much of the material well worn and quite inadequate for further use. Only the extensive bibliographies at the ends of the chapters may prove of real value.

One of the stated aims of the book is to make members ". . . of the scientific community . . . more adept at predicting what will occur in the environment as a result of some planned activity." Such activities, of course, are principally the release of chemicals into the eco-system. Although the book does an adequate job of describing various models for making such predictions in qualitative terms, it hardly lives up to its goals of making us more adept. We gain appreciation, rather than expertise.

On the positive side, the book presents throughout a much needed industrial view of environmental regulations and public policy regarding environmental impacts of industrial activity. A fair and balanced account of the PCB problem is presented, and the atmospheric fluoro-carbon controversy is discussed in detail and then related somewhat sketchily to possible models. On occasion the author becomes a bit strident, but no more so than most of us, in dealing with regulatory red tape.

Finally, the book is printed by photo-offset from a typewritten manuscript. Although the

type is clear and easy to read, and the illustrations and tables quite comprehensible, the proof reading and editing leave much to be desired. There are numerous typographical and spelling errors which proved to be very annoying.

This is not a book for the average chemical engineer. For those with training in environmental matters, it is mostly too elementary to bother with; for those with little background in this area, it may be a useful, though greatly simplified, introduction. Those willing to follow up on the bibliography may well learn a great deal. □

### **NUCLEAR CHEMICAL ENGINEERING**

*By Mason Benedict, Thomas Pigford, Hans Levi*  
*McGraw-Hill Book Company*

**Reviewed by**  
**Herbert S. Isbin**

**University of Minnesota**

Impressive in scope, details, and thoroughness! This text maintains a high concentration of rewarding material per page for approximately 1000 pages. Not surprising when one considers that three internationally recognized authorities have pooled their expertise into a skillful accounting of theory and practice for the nuclear fuel cycle. Manson Benedict (Professor Emeritus, MIT), a most distinguished elder in nuclear chemical engineering, has long been recognized for his abilities to focus on significant features and problems and to write in a remarkably clear and stimulating manner. Coauthors are Thomas H. Pigford (Professor of Nuclear Engineering at the University of California, Berkeley) and Hans Wolfgang Levi (Director of the Hahn-Meitner-Institut für Kernforschung in Berlin and APL-Professor of Nuclear Chemistry, Technische Universität Berlin). Further, the contributions of many professional colleagues in the United States and in Germany are acknowledged, reinforcing the prestigious technical input for this text.

The first of the fourteen chapters designates the chemical engineering needed to sustain the nuclear fuel cycle for the fission power reactors. Even though the purpose of the first chapter is to establish an overall perspective, quantitative details are provided in the flow sheets. The next two chapters, with emphasis on nuclear reactions and specifics of the fuel cycle, develop degrees of sophistication seldom achieved in other complete texts.

**Continued on page 85.**

**NORTH AMERICAN ASSISTANCE****P. L. SILVESTON***University of Waterloo  
Waterloo, Ontario, Canada*

**T**OWARDS THE MIDDLE OF March about two years ago, as night was beginning to fall, I stepped from the pavillion of the spanking new guest house at the University of Lagos and wandered in the warm, fragrant evening air some 50 yards down a dirt road that led to the lagoon. The horizon was still an azure blue and silhouetted the palms that bordered this broad body of water. The rising moon dappled the undulating water; the lights of Lagos flickered off to the north. Ripples lapped gently at the shore. What a difference from Canada where I had been just a few days before. Toronto was then in the midst of a snow storm and my colleagues probably were still digging out. It wasn't to be the last snow storm of the year either.

Here I was in Nigeria, West Africa's most exciting and exuberant country, to do my bit for the Third World. I was to initiate a program of assistance that had been agreed upon between my department in Canada and the department of chemical engineering at the University of Lagos. Lagos had that year begun a graduate program in chemical engineering, even though its undergraduate program had been underway for just four or five years. The department needed staffing help for this venture, and they also needed some assistance in organizing their process design course. The plan was to have a different Waterloo faculty member spend a 4 month term there each year, offering at least one graduate course and assisting with the organization of research projects and the supervision of graduate students. Arrangements of this

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**The subcommittee on Assistance to Chemical Engineering Education in the Third World is looking for members and welcomes those who will offer an active involvement in projects and project initiation . . .**

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**Peter Silveston**, professor of chemical engineering at the University of Waterloo for 18 years, is a 1951 graduate of M.I.T. He studied engineering and hitch hiking in Germany during the 50's before choosing the former as a career and the latter as an avocation, but in a guise politely referred to as "academic travel". Thus, Professor Silveston has accepted assignments in Nigeria, France, Germany, South Africa, England and the United States. His research interests are primarily in the field of reactor engineering, while his recreational passion is the Canadian wilderness wherever it can be found in Southern Ontario.

type, though often supported by government funds, have been made between other schools for many years and are not at all unusual. Most participants find assignments in the Third World satisfying and enjoyable. Certainly, I found my four months memorable and intellectually stimulating. Perhaps I contributed in a small way to the Lagos program.

Notwithstanding such satisfaction, I was dismayed at the cost and bothered by the suspicion that there are better ways of assisting education than bringing in a Westerner for a term, or even two, of teaching. Although I've brought my suggestions for improving the assistance program to the attention to my colleagues, it seems to me that some sharing of the experience would be useful on an inter-institutional basis. Perhaps there are programs the AIChE could develop, promote or sponsor. Unquestionably, helping chemical engineering grow in the Third World is a responsibility we should take on. The question is how to help most efficiently. These questions are behind the organization of the new subcommittee on Third World Chemical Engineering Education undertaken this

Continued on page 82.

# THIRD WORLD... *Two Views*

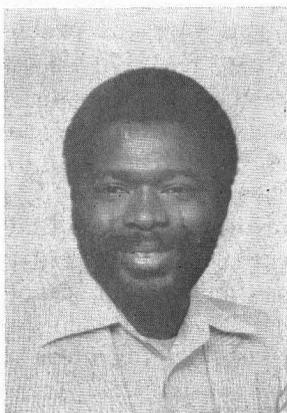
## NEED FOR INTERNATIONAL COOPERATION

H. K. ABDUL-KAREEM

*University of Lagos  
Lagos, Nigeria*

**“WE** HAVE REACHED THE moon, but we have not yet reached each other,” U Thant, former Secretary General of the United Nations, remarked at the 25th anniversary of the United Nations. I would like to believe that the AIChE's Chemical Engineering Education Projects Subcommittee on Third World ChE Education would like to help us reach out to each other. However, I note that all the members of the subcommittee are from North America. This is hardly a good beginning. If there is to be cooperation rather than charity, there should certainly be members from the Third World on the subcommittee.

Cooperation in education between the developed and still-developing sections of the world is, I be-



**Hussain K. Abdul-Kareem** graduated B.Sc. (1973) Chemical Engineering at the University of Ife (Ile-Ife, Nigeria). After graduation, he was posted to the Bendel Textile Mills (Asaba, Nigeria) as a Chemical Engineer/Quality Controller for a year for his National Youth Service, at the end of which he worked, briefly, with the former I.C.I. (Nigeria) Limited as a Chemical Sales Representative. He received his M.A.Sc. (1975) and Ph.D. (1978) at the University of Waterloo and returned to Nigeria as a Lecturer at the department of chemical engineering, University of Lagos. His research interests include forced cycling of chemical processes and the cleaning of coal. He is currently in charge of industrial training of chemical engineering students at Lagos. A member of a number of professional associations, he is also a member of the University of Lagos Senate.

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**My purpose in this paper is to bring to the attention of chemical engineering educators the problems that Third World engineering teaching institutions face and also to make some suggestions toward solutions.**

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lieve, worthwhile. After all, two-thirds of the global population live in the Third World. If we are to achieve a secure and peaceful world, something must be done to raise the living standard toward that now enjoyed by the developed nations.

The countries of the industrialized world have the resources to help raise living standards. They control about 88% of the world's wealth. Direct aid is needed, but cooperation is also very, very important. I believe cooperation is particularly important in education. The industrialized world will certainly find that the Third World has one or two things to teach them. Furthermore C. R. Fay points out, in his book entitled "Co-operation At Home And Abroad," that cooperation is to charity (aid) as prevention is to cure. I believe this statement is quite appropriate to engineering education in the Third World.

My purpose in this paper is to bring to the attention of chemical engineering educators the problems that Third World engineering teaching institutions face and also to make some suggestions toward solutions.

One would think from reading the popular press in the U.S. or in Canada that Third World problems are only debated here. Nothing could be further from the truth. We of the Third World have not been idle, nor are we idle now. We are striving hard to improve our lot. My country as well as many others have enormously expanded our educational resources since independence. Unfortunately, some of this expansion has been misdirected. This misdirection in our educational policy has resulted in millions of unemployed educated people and, at the same time, we are crying "shor-

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tage of manpower!" This definitely points to one of the problems. There are various ways by which this misdirection of education can be corrected. Policies have to be reformed in such a way, as the World Bank puts it, that they may better contribute towards economic development. This means education must emphasize skills and technical training.

Chemical engineering has been introduced as a program in many of the universities of Third World countries now pursuing industrialization. Nigeria now has 5 departments (Lagos, Ife, Port Harcourt, Benin, Ahmadu Bello) and there are jobs for all of our graduates. The discipline, therefore, is playing a role in our development.

Let me talk about some of the problems we face. Although my experience is just with my own country, I believe it is also typical of other universities in developing countries. Some of the problems that face chemical engineering departments are:

- shortage of faculty
- inadequacy or lack of support services
- shortage of teaching and research equipment
- inadequacy of research funding
- lack of administrative experience
- negative attitude towards work
- isolation from centers of technical activities

The problems are not necessarily listed in order of priority.

The staffing problem is not limited to the Third World; there are other challenging and better-paying opportunities open to qualified chemical engineers in the private sector everywhere. However, the problem is more acute in the developing nations. In my own position I could certainly double my salary by taking an industrial engineering job. Furthermore, benefits outside of salary are much better in industry. Because of shortages, benefits are more important in developing nations than in the West. This situation makes it very difficult for universities to recruit faculty, although once employed their turnover is no worse than elsewhere in the world.

One solution to this recruitment problem is for North American and European institutions of higher learning to increase the intake of Third World students into graduate programs. The trend among Western countries to increase fees for foreign students should be discouraged. The increase in revenue for the university is very small and is hardly worth the damage it does.

There is a problem with students' staying on in their host countries. This can be handled by regu-

lations which discourage foreign students from taking up academic appointments on completion of their programs. The staffing problem can never be solved by arrangements whereby faculty members from universities in industrialized countries are seconded or go on sabbatical to departments in the Third World. For purposes of teaching, this is an expensive exercise and the money would be much better spent on support services. For research, guest faculty do not serve any useful purpose because they lack basic knowledge of local problems and working in the local environment. I believe chemical engineering research in the Third World should be geared to solving local industrial problems rather than for the purpose of scholarly publications. We cannot afford the luxury of scholarship. Thus, the visiting professor who does not know the industries in the country is not in a position to provide suitable research problems or to supervise graduate students.

The problem of lack of ChE staff is being tackled by some institutions in the Third World that have started their own graduate program. This effort is, however, being thwarted by some or all of the other enumerated problems. We can all imagine a graduate program in chemical engineering without proper support services, inadequate or obsolete equipment, a shortage of research funds and the ancillary problems. Such a program will be plagued with problems.

Sabbatical arrangements can help, but they should be in the opposite direction until our chemical engineering departments are further developed. Sabbaticals in the West serve a dual purpose. The visiting faculty from the Third World can bring himself up-to-date in his field of chemical engineering, he will have the opportunity to use equipment that is not available in his home university, and he will have the valuable opportunity of exchanging ideas with faculty members of his host institution. Access to the literature provided by good libraries and the computer facilities are also some of the advantages that he will enjoy. During his stay, lecture notes can be brought up-to-date and he can help his colleagues at home with reprints or xerox copies, supplies that are often so time-consuming to get in Africa or Asia.

The problem of inadequacy or lack of support services is as serious as the previous one. Technicians capable of fabricating research or teaching equipment are not available. Universities do not recognize these skills and so we cannot compete with industry for good people. Even if technicians

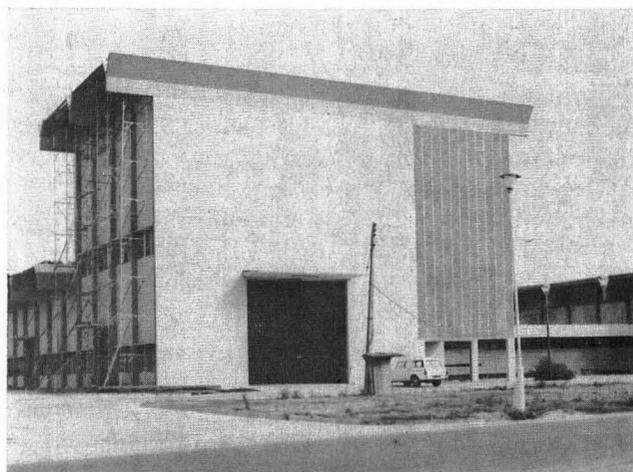
are available, there is the all-too-usual lack of an adequate machine shop, or spare parts cannot be obtained. A damaged piece of equipment is better discarded. It is easier and often cheaper to replace it because of lack of spare parts or the technical know-how required to fix it. The problem of spare parts is very acute. This is an area, I believe, where the expertise of European and North American chemical engineering departments can help a great deal. The right spare parts to be stocked for specific pieces of equipment could be recommended by your technicians and storekeepers. If we know what we need, provision can be made when equipment is purchased. A solution to the above problems which I strongly recommend is to set up sabbaticals or apprenticeships for our technicians and storekeepers in your chemical engineering departments. Exchanging technicians would also be useful, but it would suffer from the same problems I have observed with visiting professors from the West.

The problem of inadequate equipment is really a problem of funding. I will, therefore, discuss these two problems together.

Most of the chemical engineering departments in the developing world are inadequately equipped either for teaching or for research. This is a result of both insufficient grants to the universities at large and the attitudes of the existing industry in the country. One would expect developing nations to encourage their institutions of higher learning to expand for the purpose of producing the trained manpower for nation-building by adequately funding these institutions. But this is not the case for reasons which are, at times, beyond the control of government itself, or simply due to the gross misplacement of priorities. Government is not the only problem. A rather saddening observation of mine and many others in both industrialized and industrializing nations is the unpatriotic attitudes of many foreign-owned industries operating in the country. Despite the huge profits they declare—never mind the undeclared ones—and the foreign earnings they make for their home countries, these foreign-owned companies never deem it fit to cooperate with the educational or research institutions in the nations where they garner their profits. I strongly believe that the Chemical Engineering Education Projects Committee can and, indeed, should encourage companies with overseas branches to fund research in those Third World nations where they operate. Actually, I do not think it will be out of place if our governments

made it mandatory for all companies operating in our countries to fund research with a fixed percentage of their annual profit. It is equally saddening to see manufacturers of research equipment selling outdated and or dilapidated equipment to research institutions in the Third World. At times we feel we are used as guinea pigs with untested equipment.

As the word "developing" implies we have not yet arrived, so our administrative experience and our attitudes towards work are not quite what they ought to be. The universities and other advanced teaching institutions, as citadels of learning, have a sacred duty in this regard. We should be setting



**Chemical engineering building, showing the high head room laboratory and faculty office wing, University of Lagos**

the standard in providing good administration. Lack of administrative skill is acute at the technician/storekeeper level and training in North America could really help. Even a better attitude towards work could be fostered. Officers in the university service departments such as grounds, finance and bookkeeping need training, but this is a university job and not one for chemical engineering departments.

The development of one of the very important support services—the library—can help solve our problem of isolation from the centers of technical activities of the world. Our libraries are poorly stocked with the literature relevant to research and teaching and they do not receive their periodicals and journals on time due to poor communication between countries. Most universities do not have sufficient funds to buy all the journals or books which are needed. Perhaps the AIChE through the ChE Education Projects Committee

could raise funds to provide subscriptions to chemical engineering departments of developing nations. Could the AIChE donate their publications package to Third World departments? Third World participation in the ChEEP. would also help us stay in touch.

The location of most international chemical engineering conferences, seminars, and the like, are too far away from the Third World countries. The exorbitant cost of transportation makes attendance from the Third World virtually impossible. The importance of these meetings to the development of engineering education cannot be overemphasized. They provide, among other benefits, opportunities for frequent exchange of ideas and ensure up-to-date knowledge of current developments in the technical field. There are, and can only be, very few such meetings in the Third World because of the newness of the discipline and the small number of institutions offering chemical engineering as a course. I believe the AIChE, through the ChE Education Projects Committee, should consider arranging seminars at least annually in a developing nation with the cooperation of Third World chemical engineering departments and perhaps UNESCO. Seminars could help solve the problem of isolation. I am sure that Canadian and U.S. professors would welcome a chance to spend a week in Nigeria at a seminar instead of going to New Jersey or Ohio.

In conclusion I will mention a "reaching out" exercise that I am participating in. Canada, under the auspices of the Natural Science and Engineering Research Council and the Canadian International Development Agency (NSERC/CIDA), has established a fellowship program whereby faculty members from developing nations are given the opportunity to work with faculty members in Canadian universities on a joint research project. These fellowships are valid for a period of three months for three consecutive summers. The United States also has such a scheme, known as the Fullbright Award program. However, the U.S. program is for a single period of four months only.

I have found participation in the Canadian program very rewarding. It has provided an opportunity to discuss curriculum and textbooks with my Canadian colleagues. I have also had the opportunity to review new books that have not yet reached Nigeria and to order supplies that would ordinarily take many months to reach us. Travel funds are available so that other schools can be

visited and so that I can attend at least one technical meeting. The program also provides the opportunity to see what research is underway in the host university and to discuss my research projects with my hosts. Unfortunately, three months is just too short a time to accomplish much on a research project, even with equipment available and operating. This is true even though the Canadian program usually sends the faculty member to the school which he studied at, in order to avoid the orientation period.

The problems with these two programs are the interruptions in the Canadian fellowship and the shortness of the U.S. fellowship. I believe an arrangement whereby the recipient of the award and his family spend a whole academic year in the host country would better serve the purpose of these programs. The programs are in the right direction, however. Also in the right direction is a new cooperative program established by the International Development Research Center (IDRC) in Ottawa, Canada. This program funds research in Canadian universities on problems relative to development in Third World countries. Researchers can be Canadians or a team with membership from the target developing country. Time will tell how successful the program will be. If administered well, it could make a real contribution. The Canadians have set the ball rolling and we can and will reach each other. □

## **NORTH AMERICAN ASSISTANCE**

**Continued from page 78.**

year by the AIChE's Chemical Engineering Education Projects Committee.

What are projects which could be undertaken in place of, or to supplement visits of chemical engineering educators? Let me begin discussion of this question by outlining some of my observations. The experience of the Lagos faculty lies heavily in the areas of chemical reactor analysis, catalysis, and kinetics; it's not surprising that many of the initial projects selected for graduate study reflect this experience. Modern work involves reasonably sophisticated analytical equipment. Often the productivity of a research student can be enhanced enormously by semi-automated reactors. Nigeria's oil wealth and the heavy emphasis the government has put on education means money is available for the purchase of quite sophisticated equipment. During my short stay I had the frustrating experience of trying to help faculty and technicians set up and shake down some of the units that had ar-



Engineering faculty buildings, University of Lagos

rived. Certainly there is no area of greater frustration for a Westerner in the Third World than trying to build and operate experimental equipment. Regular failures of electric power, water shut-downs, and air conditioner failures coupled with high humidity and dust are often second order problems. In Lagos, primitive port facilities, inept customs handling and road conditions mean that the equipment arrives in the laboratory needing immediate repair. There are, however, no maintenance facilities or parts depots in West Africa. Not only must everything be shipped in from Europe or North America, but clearance for expenditures in foreign currency must be obtained even for the most meager spare part. Parts cannot be fabricated locally because shop facilities are inadequate and a good part of the technicians' day must be spent ferreting out parts or supplies. When something *is* found it goes into a file cabinet and its existence is treated as a state secret.

The crying need in Lagos (and I suspect in many new Third World chemical engineering departments) is for reliable support services: a storeroom stocked with basic parts, spares for key components of departmental equipment, up-to-date stock lists, a continuing budget for replacements, and above all a well trained storekeeper. Lagos has a basic shop adequate for fabricating supporting structures, but it is inadequate for fine machining. No electronics shop exists and virtually no equipment is available for circuit testing and electronics trouble shooting. Lagos has a good complement of technicians, but they seem to interface poorly with research students and faculty. One-on-one supervision was necessary. The Lagos department is well supplied with office help, messengers and driv-

ers, but management is poor and supervision of simple matters like note typing and duplicating falls upon faculty. Assistance is desperately needed for the training of the support staff. Probably some sort of apprenticeship in our institutions would be better than sending Western technicians to train staff in Third World institutions. At Waterloo we are searching for funds to bring storekeepers and technicians from Lagos to Canada for, say, a two to six month period to work as assistants to their counterparts here.

Nigerian universities, concerned about establishing scholarly standards comparable to those in the developed world, have promulgated advancement standards in terms of research publications that are laughably unrealistic in terms of the difficulties of initiating and maintaining research. Promotion seems slow. This is unfortunate because there are lucrative opportunities in the private sector to tempt faculty. Indeed, faculty turnover is high.

One way of surmounting the problem of maintaining research is to invite junior faculty members to work in research groups in North American departments. Canada has already initiated an effort in this direction: graduates of Canadian institutions in Third World teaching positions are given three month fellowships for each of three years, which permit them to return to Canada (usually their home institution) for further research.

The teaching of process design is enhanced by using the technical literature of equipment manufacturers. For some reason, literature of this type is virtually unattainable in the Third World. We are tackling this problem at Waterloo by ordering extra literature, beyond the number needed for our own program, and providing it at cost to Lagos.

Are there alternatives to bringing faculty from developed countries? In many areas, visiting faculty are high priced because of salary, or the size of the family which must be transported and housed, or because of living style expectations. Some courses (process design, for example) should have some relevance to the host country. It should reflect the level of current technology or at least the near technological horizon. Thus, the instructor must have a reasonably good knowledge of the major industries of the country, their technologies, and projects planned for the near future. It is rare for visiting faculty to have such knowledge. Advising research students in Third World institutions has its pitfalls also. Lack of simple parts,

equipment maintenance problems, and limited experience of technicians puts different constraints on what experimental programs can be undertaken than those met in North America or Europe. It is difficult for visiting faculty to know what is a reasonable problem for a student under such conditions.

A better alternative might be to bring junior faculty to North American institutions and place them as "interns" in team teaching situations or in team research supervision. Lagos could have sent two of their staff (with families) to Waterloo for four months for the same cost to them of my visit for the same length of time.

The number of North Americans who have taken part in educational programs in the Third World is surprising. These have either been sabbatical leaves spent where the host country bears all or part of the cost, or assignments undertaken

**TABLE 1**

**Proposals for Assisting ChE Education in the Third World**

1. Apprenticeships for storekeepers, technicians in North American ChE departments or research institutes  
*Objective: improve support services for teaching and research*
2. Sharing of company reference material used for process design courses  
*Objective: enrich process design teaching*
3. Summer research fellowships in North America for junior faculty from Third World institutions  
*Objective: assist faculty development*
4. Development of a final year/postgraduate course on development problems, appropriate technologies, development strategies for the Third World\*  
*Objective: mitigate ignorance of our graduates of the problems of this important part of the world*
5. Development of a co-op engineering program with multinational corporations operating in the Third World for Third World engineering students\*  
*Objective: improved engineering education, manpower supply for multinationals*
6. Preparation of course material on construction and operating costs in Third World countries\*  
*Objective: improve teaching materials for engineering economics courses, supply data for North American organizations*
7. Teaching internships for Third World ChE faculty in North American departments  
*Objective: course development, teaching skill development*

\*Proposals originated by Professor W. H. Tucker, Tri-State College, Indiana.

on behalf of United Nations agencies, or those established through aid programs on intergovernmental levels. If you have not taken an overseas assignment, it's quite likely that one of your colleagues has. Certainly, a great deal of experience has been collectively accumulated by North American faculty. The new subcommittee on Assistance to Chemical Engineering Education in the Third World hopes to tap this experience and, further, is looking for your ideas. The subcommittee would like to know about current as well as past programs. It is interested in those which were successful and those which did not seem to work out. Areas where the AIChE could help, of course, will be sought. The subcommittee will also be looking for programs that individual departments could undertake, or even those which solicit contributions from individual faculty members.

A survey of North American faculty is planned to identify and summarize the experience available and to solicit ideas. Some proposals have already come in. They are summarized in Table 1 along with those just mentioned. It is hoped that the subcommittee will eventually undertake projects. Perhaps some will lead to AIChE activities; others may stimulate action by our teaching institutions. For the moment, the subcommittee plans to pursue study, discussion of problems, and proposals, with results emerging as reports.

The subcommittee has begun with a few enthusiasts—but in order to make a useful contribution, wider participation is needed. The subcommittee on Assistance to Chemical Engineering Education in the Third World is looking for members and welcomes those who will offer an active involvement in projects and project initiation, as well as those whose role will be more passive, through sharing of their experience and constructive advice. □

*Author's Note: The results of the ChE Education Subcommittee survey begun in 1981 are now in, showing that 10% of the chemical engineering teaching staff in the U.S. and Canada has participated in teaching research or training programs in Third World countries.*

*Survey results show that the proposal to assist development of support staffs by providing apprentice type training to technicians, storekeepers, etc., for periods of a few months to a year elicited 77 responses; 27 departments would participate in such a program, 23 felt they did not have suitable facilities or personnel to do so, and the remainder wanted further details. Only one department would contribute financially to the apprenticeship, and forty indicated funding would have to come entirely from external funds.*

*The second proposal was to invite Third World teaching*

faculty to take sabbaticals in North America. 78% of the respondents said they would participate in such a program, but 45% of them would want the program to be funded externally.

The third proposal, to invite PhD graduates with Third World degrees to do one or more postdoctoral years in North America, was less enthusiastically received. 57% of the responses indicated participation and 17% would not be interested. 27 departments would like to see separate external funding and an equal number felt that some support could come from ongoing contracts or programs in their departments.

The Third World Subcommittee is now chaired by Prof. C. J. Barr, California State Polytechnic University, Pomona. He would welcome your suggestions and inquiries.

## BOOK REVIEW: Nuclear ChE

Continued from page 77.

Chapter 4 lays the foundation for solvent extraction and systems are selected for illustrating principles and practice. Included is a brief accounting of the types of commercial equipment.

Uranium, thorium and zirconium have separate chapters devoted to the physical and chemical properties of the element and its compounds and the associated processing.

Chapters 8, 9 and 10 deal with the processing of irradiated fuel and materials. The identification of the radionuclides of interest and the time-dependent behavior in and out of the reactor are presented and illustrated in Chapter 8. Detailed information on plutonium and other actinide elements (proactinium, neptunium, americium and curium) is given in Chapter 9, and Chapter 10 is devoted to fuel reprocessing. Both U.S. and overseas reprocessing plants are noted. The lack of an operating commercial reprocessing plant in the United States has perhaps placed an undue emphasis on the design calculations for the Barnwell Nuclear Fuel Plant.

Rightfully, radioactive waste management is singled out for Chapter 11. The focus, however, is primarily on high-level wastes. A "most recent estimate of the amount of solidified high-level wastes to be accumulated at a federal repository in the United States..." turns out to be a 1976 reference with an over-optimistic projection of nuclear power and the achievement of the repository. The authors have recognized the uncertainties in the projections and sought to place in perspective the relative magnitudes of the volumes and curies of the high-level wastes with respect to the natural radioactivity in the earth's crust. Nevertheless, this outdated reference serves to

illustrate the practical difficulties in updating the material for this work.

Isotopic separations are the topics for the last three chapters. Methods and principles are given for stable isotopes in Chapter 12. Chapter 13 presents processes for the separation of isotopes of hydrogen and other light elements. The final chapter is on the separation of uranium isotopes.

In my judgment, the authors have provided a wealth of technical information on the nuclear fuel cycle and have been successful in highlighting important principles and in providing meaningful illustrations. Each reviewer, however, may seek to augment this outstanding contribution with still more features. For example, elements of safety and the protection of the public health have been interwoven into the various chapters, but on too modest a level from my point of view. What is needed is an additional chapter on safety. What are the special approaches used to cope with the impact of this new industrial development upon society? What are the guiding safety philosophies and regulatory requirements? What are the techniques that can be used to identify and evaluate risks? Is there a new emerging role for the engineer to be more responsive to societal issues in providing inputs for evaluating acceptable risks? □

## ALTERNATIVE FUELS: CHEMICAL ENERGY RESOURCES

By E. M. Goodger

John Wiley & Sons, NY, 1980

Reviewed by H. H. Lee  
University of Florida

This is a useful reference for those who would like to get a broad picture of alternative fuels as well as for those who want some pertinent data in certain specific areas. Fuel specialists may find it useful in relating their area of specialty to the overall picture of alternative fuels. As the author adequately puts it, the book is offered as one convenient format for the collocation and analysis of relevant data scattered about the literature.

The alternative fuels considered in this book are those intended for oxidation only and so the wider field of alternative energy sources such as wind, tides, geothermal, direct solar radiation and nuclear fusion is excluded from consideration. It deals with alternative ways of using conventional fuels by modifying the forms and ap-

Continued on page 88.

## DISTILLATION CALCULATIONS WITH A PROGRAMMABLE CALCULATOR

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**T**HE CONCEPTS OF MINIMUM reflux ratio and optimum feed tray location in distillation problems involving more than two components are somewhat more difficult for students to grasp than are these concepts applied to two-component systems. These concepts can be developed from fundamentals by considering zones of constant composition and ratios of key components, using either analytical solutions (such as the Underwood equations) or stage-to-stage calculations. They can also be developed with the use of computers by calculating and plotting results for the distillation of a particular multicomponent system for a specified separation of various reflux ratios and various feed tray locations. The concept of minimum reflux ratio becomes very real when mole fractions  $<0$  or  $>1$  appear in printouts.

One reasonable way to approach the teaching of multicomponent distillation to undergraduates is in three steps:

1. Develop equilibrium relations and operating line equations for the simplest case of constant relative volatility and constant molal flow rates of liquid and vapor streams.
2. Assign students to study patterns of distribution by performing stage-to-stage calculations for a specified separation of a four-component mixture at several reflux ratios (including at least one below the minimum) and several feed tray locations.
3. Generalize the results of student calculations and develop criteria for minimum reflux ratio and optimum feed tray location.

The emphasis here on a study of patterns of

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**The concepts of minimum reflux ratio and optimum feed tray location in distillation problems involving more than two components are somewhat more difficult for students to grasp . . .**

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**Bret L. Halpern** received his PhD from the University of Chicago and is currently an Assistant Professor. He has had experience in surface science and catalysis at the University of Missouri (Rolla) and the Universite de Lyon (France). His main research interest is the dynamics of surface-catalyzed reactions, and he teaches courses in chemical engineering laboratory, electrochemistry, and water quality control. (R)

distribution as an aid to understanding separation processes is in accord with C. J. King's approach as outlined in his book on separation processes.

Step 2 of this approach can also be carried out handily with programmable calculators, providing students with the convenience of studying anywhere they please rather than having to seek out a computer terminal. The time required with a programmable calculator is quite reasonable. With the programs developed here it is possible to perform calculations for several cases in the course of one evening.

Consider the distillation of a six-component mixture.\* Assume constant relative volatility and constant molal overflow. The basic equations can be written as follows:

\*The TI-58C provides enough memories and program steps for more than six components.

$$y_i = \alpha_i x_i / \sum_{i=1}^6 \alpha_i x_i$$

$$x_{i,m+1} = \frac{\bar{L}-b}{\bar{L}} y_{i,m} + \frac{b}{\bar{L}} y_{i,b}$$

$$x_{i,n+1} = \frac{L+d}{L} y_{i,n} - \frac{d}{L} x_{i,d}$$

Here the operating lines have been written in the form convenient for calculations up a column, beginning at the stillpot. These equations contain 20 constants for the six-component case for a given feed composition, feed condition, desired separation, and reflux ratio.

Register assignments and programs for stage-to-stage calculations on the distillation of a six-component mixture are presented in Table 1. Note that registers 01-06 are reserved for storing successive values of  $x_i$  and  $y_i$ . These values can be recalled as needed for recording or plotting. Programs in Table 1 are also suitable for calculations on 2-, 3-, 4-, or 5- component mixtures provided

zeroes are stored in registers designated for the missing components.

The use of these programs for a case where the bottoms product composition is known is straightforward. After placing values of  $x_{i,b}$  in registers 01-06, depressing key A will result in calculation of the composition of vapor leaving the stillpot. Depressing key D then yields the composition of liquid leaving the first tray above the stillpot. Alternating between keys A and D is thus all that is needed to calculate up the column. Calculations above the feed tray consist of depressing keys A and A' alternately.

As an example of the use of these programs consider a simple case of distillation of a four-component mixture.

Component	mole % in feed	Relative volatility
1	40	2.7
2	20	1
3	15	0.76
4	25	0.35

**TABLE 1**  
Six-Component Distillation Calculations  
TI-58C Programmable Calculator  
(Partition to 239/29)

ASSIGNMENTS OF REGISTERS	EQUILIBRIUM CALCULATION	OPERATING LINES	
		Stripping	Rectifying
01 $x_1(y_1)$	2nd Lbl A	2nd Lbl D	2nd Lbl A'
02 $x_2(y_2)$	0	6	6
03 $x_3(y_3)$	STO 13	STO 00	STO 00
04 $x_4(y_4)$	6	20	27
05 $x_5(y_5)$	STO 00	STO 13	STO 13
06 $x_6(y_6)$	12	2nd Lbl E	2nd Lbl B'
07 $\alpha_1$	STO 28	RCL 14	RCL 21
08 $\alpha_2$	2nd Lbl B	2nd Prd 2nd Ind 00	2nd Prd 2nd Ind 00
09 $\alpha_3$	RCL 2nd Ind 28	RCL 2nd Ind 13	RCL 2nd Ind 13
10 $\alpha_4$	2nd Prd 2nd Ind 00	SUM 2nd Ind 00	INV SUM 2nd Ind 0
11 $\alpha_5$	RCL 2nd Ind 00	1	1
12 $\alpha_6$	SUM 13	INV SUM 13	INV SUM 13
14 $(\bar{L}-b)/\bar{L}$	1	2nd Dsz 0	2nd Dsz 0
15 $(b/\bar{L})x_{1,b}$	INV SUM 28	E	B'
16 $(b/\bar{L})x_{2,b}$	2nd Dsz 0	R/S	R/S
17 $(b/\bar{L})x_{3,b}$	B		
18 $(b/\bar{L})x_{4,b}$	6		
19 $(b/\bar{L})x_{5,b}$	STO 00		
20 $(b/\bar{L})x_{6,b}$	2nd Lbl C		
21 $(L+d)/L$	RCL 13		
22 $(d/L)x_{1,d}$	1/x		
23 $(d/L)x_{2,d}$	2nd Prd 2nd Ind 00		
24 $(d/L)x_{3,d}$	2nd Dsz 0		
25 $(d/L)x_{4,d}$	C		
26 $(d/L)x_{5,d}$	R/S		
27 $(d/L)x_{6,d}$			

The overhead product is to contain 99 mole % A, and the recovery of A is to be 99%. With these specifications it is reasonable to assume that the overhead contains only A and B, and a good estimate of the bottoms composition can be made:

$$\begin{aligned}x_{1,b} &= 0.0067 \\x_{2,b} &= 0.3267 \\x_{3,b} &= 0.2500 \\x_{4,b} &= 0.4166\end{aligned}$$

A first assignment for calculations in this case could be as follows:

1. For a reflux ratio in the range  $L/d = 1 - 2$ , calculate up the column until a zone of constant composition is reached. Prepare a plot of liquid composition vs. plate number. Select a reasonable tray for introducing the feed and calculate up the column to the product composition. Try two more feed tray locations. Which choice of feed tray requires the minimum number of trays for the specified separation?
2. Study the effect of decreasing  $L/d$ . Try a series of values until you reach a value where the specified separation can not be achieved. What happens?
3. Rewrite the problem for a case where a split is to be made between components 2 and 3. For example, specify that recovery of B in the overhead is to be 99% and recovery of C in the bottoms is to be 99%.

With these exercises behind them, students are well prepared for more formal developments of multicomponent distillation calculations.

The results of calculations for a reflux ratio ( $L/d$ ) of 1.2 are summarized in the Table below and in Fig. 1. Tray 8 was selected as the feed tray after inspecting a graph of tray number vs. mole fraction in which calculations were performed from still to a pinch region (at about tray 18).

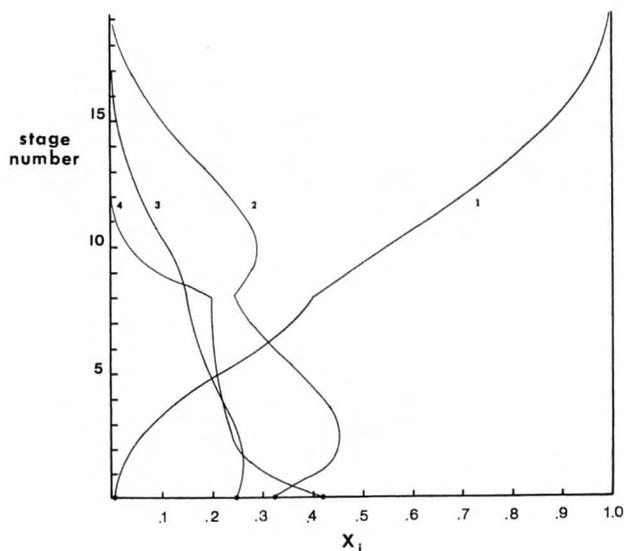


FIGURE 1. Results for  $L/d = 1.2$

#### Summary of Results for $L/d = 1.2$

Tray number	$x_1$	$x_2$	$x_3$	$x_4$
Still	0.0067	0.3267	0.2500	0.4166
2	0.0410	0.4531	0.2574	0.2485
4	0.1417	0.4205	0.2174	0.2204
6	0.3001	0.3181	0.1756	0.2061
8	0.4058	0.2449	0.1516	0.1978
10	0.5676	0.2916	0.1103	0.0305
12	0.7105	0.2321	0.0542	0.0032
14	0.8402	0.1388	0.0207	0.0003
16	0.9311	0.0623	0.0066	$1.7431 \times 10^{-5}$
18	0.9814	0.0167	0.0019	$1.0564 \times 10^{-6}$
( $y_{18}$ )	(0.9932)	(0.0063)	(0.0005)	( $1.3858 \times 10^{-7}$ )

Values of  $x$  and  $y$  can be recorded for each tray, of course, but liquid mole fractions on even-numbered trays were chosen here as sufficient to define a graph of tray numbers vs. liquid mole fraction. □

*Editorial Note: A more complete set of programs providing for calculations beginning at either the top or bottom of a column is available and can be obtained by contacting either of the authors of this article.*

#### NOMENCLATURE

- $x_i$  = mole fraction of  $i$ th component in liquid.
- $y_i$  = mole fraction of  $i$ th component in vapor.
- $\alpha_i$  = relative volatility of  $i$ th component.
- $L$  = Liquid flow rate in rectifying section, moles/hr.
- $\bar{L}$  = Liquid flow rate in stripping section, moles/hr.
- $b$  = Flow rate of bottoms product, moles/hr.
- $d$  = Flow rate of overhead product, moles/hr.
- $m + 1$  refers to plate above  $m$ th plate in stripping section.
- $n + 1$  refers to plate above  $n$ th plate in rectifying section.

#### BOOK REVIEW: Alternative Fuels Continued from page 85.

plications of these fuels, and with the unconventional fuels that can be derived from both conventional and unconventional fuels. The author then examines and compares each of the alternatives in terms of combustion characteristics, and combustion performance.

The last chapter is devoted to those fuels which appear to hold particular promise, which are coal conversion products, alcohol and hydrogen.

This book is informative and may be useful as a reference in an introductory course on fuel. □

## INPUT MULTIPLICITIES

Continued from page 63.

of  $A_5$  to regulate the product concentration of  $A_1$ , the feed concentration of  $A_6$  to regulate the product concentration of  $A_3$ , and the total feed rate to regulate the product concentration of  $A_2$ . Transients following a temporary disturbance, using proportional-plus-integral control in each loop, are shown for the outputs in Fig. 11, and the manipulations in Fig. 12.

The limit cycle is clearly demonstrated by Figs. 11 and 12 to be unconstrained. Further, the same ultimate period and amplitude is reached following a variety of disturbances. Also, the "time-averaged" behavior of the manipulated variables shows that the system has diverged to an alternate

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**The ultimate goals are twofold: first, we want to know whether indeed input multiplicity occurs in industrial systems with sufficient frequency to be of concern . . .**

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steady-state, as discussed in the previous example. At this alternate steady-state the control system is less stable, causing an initial tendency to diverge, but ultimately resulting in an unconstrained limit cycle.

The unconstrained limit cycle phenomenon is potentially very important. In contrast to "smooth" divergence to an alternate steady-state, it is quite simple to detect in an operating plant. Also, we have mathematical evidence, which will be presented below, which suggests that the same mathematical condition necessary for input multiplicity may also be necessary for an unconstrained limit cycle. Therefore, if the sudden reduction in stability is observed as a sustained oscillation, in which none of the valves or transmitters is saturated, this may be strong evidence of input multiplicity, and a good clue on how to eliminate the problem.

### THEORETICAL RESULTS TO DATE

**Relations Between Input Multiplicity and Stability.** Consider a process with steady-state behavior modelled by the equations

$$\mathbf{c} = \mathbf{f}(\mathbf{m}) \quad (1)$$

where  $\mathbf{c}$  is a vector of  $n$  process outputs,  $\mathbf{m}$  a vector of  $n$  process inputs or manipulations, and  $\mathbf{f}$  a vector of  $n$  steady-state model equations. Input multiplicity occurs if more than one value of  $\mathbf{m}$  can pro-

duce the desired value of  $\mathbf{c}$ .

Under mild restrictions, catastrophe theory (see for example Aris [1] or Calo and Chung [4,5,6]) shows that a necessary condition for input multiplicity is

$$\left| \frac{\partial \mathbf{c}}{\partial \mathbf{m}} \right| = 0 \quad (2)$$

where  $|\quad|$  indicates the determinant, and

$$\frac{\partial \mathbf{c}}{\partial \mathbf{m}} = \begin{bmatrix} \frac{\partial c_1}{\partial m_1} & \frac{\partial c_1}{\partial m_2} & \frac{\partial c_1}{\partial m_n} \\ \frac{\partial c_2}{\partial m_1} & \frac{\partial c_2}{\partial m_2} & \frac{\partial c_2}{\partial m_n} \\ \frac{\partial c_n}{\partial m_1} & \frac{\partial c_n}{\partial m_2} & \frac{\partial c_n}{\partial m_n} \end{bmatrix} \quad (3)$$

is the Jacobian matrix of steady-state gains. Roughly speaking, if Eq. (2) is satisfied anywhere in the  $(\mathbf{c}, \mathbf{m})$  space, the possibility of input multiplicity exists. The one-dimensional version of this result is quite easy to interpret (see Fig. 14).

As shown previously [7,8], the condition in Eq. (1) is closely related to the stability of the intended control scheme. These results can be briefly summarized as follows:

The components of  $\mathbf{c}$  and  $\mathbf{m}$  will each be ordered according to the intended control scheme, which is pairing  $c_j$  with  $m_j$  (for each  $j = 1, 2, \dots, n$ ) in a typical single-input-single-output control loop. This is the most widely practiced form of multi-variable process control, and the majority of the loops will contain proportional-plus-integral action. Therefore, the diagonal elements of Eq. (3) represent the open-loop process gains for the intended pairing.

A plausible control scheme is defined as one in which each of the  $n$  individual loops is operated in strictly negative feedback. To my knowledge, implausible control schemes are never knowingly operated in practice, for at least two reasons. Any loop with positive feedback cannot be individually operated and tuned, since it is unstable. And, although the entire system of  $n$  loops operating together may be stable, it is typically not sufficiently stable to give the required robust behavior in the presence of unmeasured disturbances.

The matrix  $\partial \mathbf{c}^* / \partial \mathbf{m}$  is formed from  $\partial \mathbf{c} / \partial \mathbf{m}$  by multiplying rows or columns, as desired, of  $\partial \mathbf{c} / \partial \mathbf{m}$  by  $(-1)$  as needed to produce a diagonal with all positive elements. For example, if

$$\frac{\partial \mathbf{c}}{\partial \mathbf{m}} = \begin{pmatrix} 1 & 1 \\ -1 & -2 \end{pmatrix}$$

then

$$\frac{\partial c^*}{\partial m} = \begin{pmatrix} 1 & -1 \\ -1 & 2 \end{pmatrix} \text{ or } \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix}$$

One can show [7,8] that, unless the following condition is satisfied at the desired steady state

$$\left| \frac{\partial c^*}{\partial m} \right| > 0 \quad (4)$$

there exists no set of plausible gains and reset rates which will yield a stable control system at that steady state.

The conditions in Eq. (2) and Eq. (4) are closely related. The difference between  $|\partial c/\partial m|$  and  $|\partial c^*/\partial m|$  can be at most a sign. The locus of all steady-states satisfying Eq. (2) therefore divides the space into regions in which different pairings can be stable and plausible. This observation was used [8] to map the steady-state space for the 2 x 2 control scheme, on the single  $A \rightleftharpoons R \rightleftharpoons S$  exothermal reactor, into regions in which different pairings could be stable and plausible. The results are shown in Fig. 13.

These theoretical results demonstrate why the stability level is apt to be significantly altered if the control system diverges to an alternate steady state, which is in a different stability/plausibility region. The phenomenon is explained by the close

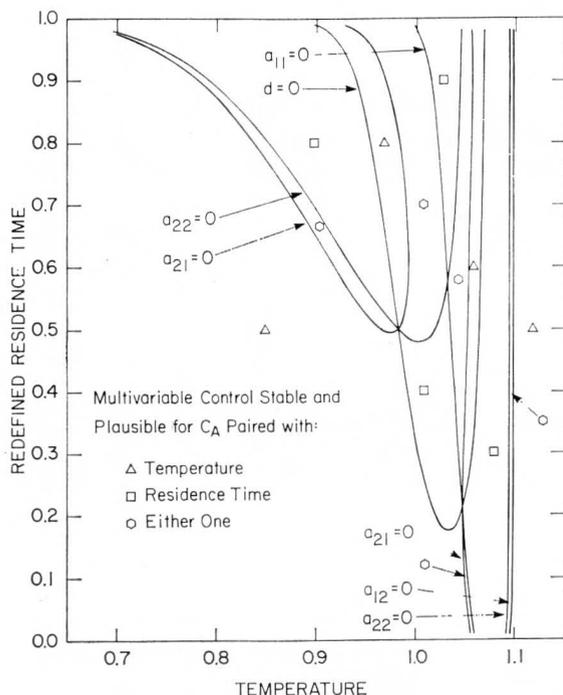


FIGURE 13. Stability/plausibility regions for 2 x 2 reactor control scheme

relation between the necessary conditions for input multiplicity and for stability/plausibility.

**Input Multiplicity and Unconstrained Limit Cycles.** The results to be discussed here are encouraging, but much more fragmentary than I would like. They are currently worked out only for a one-dimensional control system, i.e., with one input and one output, with a specific form of dynamics.

We consider a process whose dynamics are represented by the single equation

$$\frac{dc}{dt} = f(m) - c \quad (5)$$

The control will be proportional-plus integral

$$m = K_c \left[ (r-c) + \frac{1}{\tau_I} \int_0^t (r-c) dt \right] \quad (6)$$

where  $r$  is a constant set-point value. Differentiating Eq. (6) with respect to time, and substituting Eq. (5) for  $dc/dt$  into the result, yield a second differential equation

$$\frac{dm}{dt} = K_c \left[ c-f(m) + \frac{r-c}{\tau_I} \right] \quad (7)$$

Eqs. (5) and (7) form two ordinary differential equations in two unknowns, the case for which there exists the largest body of theory on limit cycle behavior.

A theorem of Bendixon [3] states the following:

If a system has dynamic equations  $\dot{x} = P(x,y)$  and  $\dot{y} = Q(x,y)$ , then no limit cycle can exist in any region of the  $(x,y)$  phase plane within which  $(\partial P/\partial x + \partial Q/\partial y)$  has an invariant sign, and is not identically zero. Applied to Eqs. (5) and (7), this says that no limit cycle can exist in any region of  $(c,m)$  space unless

$$-1 - K_c \frac{df}{dm}$$

changes sign.

If we assume plausibility, and therefore  $K_c (df/dm) > 0$  at the desired steady state, then there can be no limit cycle unless  $df/dm$  changes sign somewhere in  $(c,m)$  space. Eq. (5) shows that the steady state is  $c = f(m)$ . These observations together show that a necessary condition for a limit cycle is that

$$\frac{dc}{dm} = 0 \quad (8)$$

somewhere in the steady-state  $(c,m)$  relationship.

This is the same condition needed for input multiplicity.

The requirement for an *unconstrained* limit cycle enters in the following manner: The proof of Bendixon's theorem requires use of Green's theorem

$$\int (Pdy - Qdx) = \int \int \left( \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} \right) dx dy$$

which in turn requires that P and Q be continuous and have continuous first partial derivatives. A limit cycle operating with a saturated m or c would not be described by functions in Eqs. (5) and (7) which satisfied these conditions.

These fragmentary observations give encouragement about the relation between input multiplicity and unconstrained limit cycles. In this specific example, similar conditions on the steady-state derivatives and plausibility considerations appear to be involved in both phenomena. More investigation is warranted to determine the full extent of the connection between input multiplicity and unconstrained limit cycles, since this could facilitate demonstration of the former by observation of the latter.

**Adjacency and Connectedness.** My experience with the phenomenon has strongly suggested that input multiplicity will not be a problem in process control systems unless there exist at least three possible steady states. Fig. 14 is sketched to support an approximate explanation of this assertion, for a one-dimensional system. The sketches are example steady-state relationships  $c = f(m)$ .

In Fig. 14 (a), three possible steady states exist for the chosen set-point value r. Of these, only 1 and 3 can be stable if a controller with positive gain is used, and only 2 is stable if a negative gain is used, because of the different signs of  $df/dm$  at the steady states. Fig. 14 (b) then suggests that, with only two steady-states, only one can be stable for a particular choice of gain. Thus, we might conclude that, unless there are at least three steady states, we need not be concerned about having the system come to rest at other than the design steady state. This reasoning explains why all the illustrative examples discussed previously have more than two steady states. We might also conclude from Figs. 14 (a) and (b) that *adjacent* steady states cannot both be stable for the same control settings, so that divergence could occur only to a non-adjacent steady state. Fig. 14 (c) is sketched to show that we have to amend this conclusion to state that two steady states which are *adjacent* and *connected* cannot both be stable for

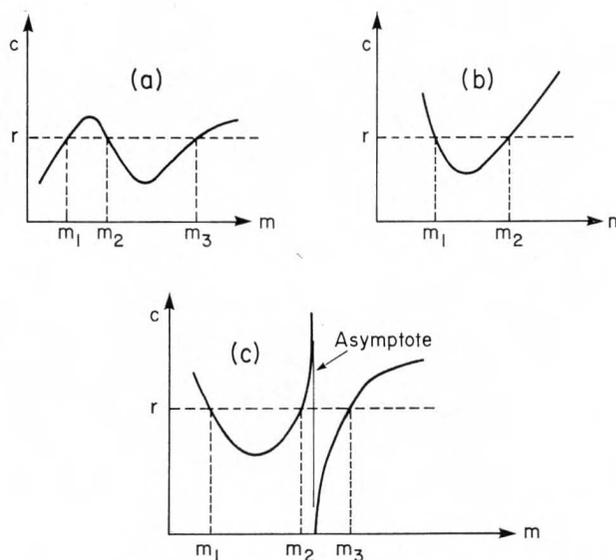


FIGURE 14. Illustrating adjacency and connectedness

the same control settings. These observations are useful for dealing with the input multiplicity problem in practical situations.

Extending these observations to systems of greater dimensionality requires further research. The first complication is the difficulty of defining and identifying *adjacency* and *connectedness* of steady states in such systems. Partial results have been obtained [10], but these are in need of sharpening. Further, in higher dimensions the strongest statement we can hope to prove is that adjacent and connected steady states cannot both be *stable* and *plausible* for the same controller settings. This would still be a powerful statement, because a stable but implausible system will exhibit a lower level of stability.

#### PLANS FOR FURTHER RESEARCH

At present, five main issues appear to be of highest priority: (1) identification of process structures likely to lead to input multiplicity; (2) detection of input multiplicity from steady-state process models; (3) detection of input multiplicity from plant data; (4) identification of the residual group of variables responsible for the input multiplicity; and (5) choice of control pairings to eliminate the multiplicities.

The ultimate goals are twofold: First, we want to know whether indeed input multiplicity occurs in industrial systems with sufficient frequency to be of concern. Assuming a positive answer, then the second goal is development of approaches for detection and elimination of the phenomenon, in

situations where it is a cause of operating problems. □

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## DEPARTMENT: Delft

Continued from page 57.

areas. Specifically, the department requires the project to consist of six students who work five to ten days as a team, to integrate at least two of the six different laboratory areas, and to be scientifically relevant or practical, remaining open-ended and constantly requiring new research ideas from the student group. Some of the research projects from a recent 27-project list include:

- Heterogeneous catalytic decomposition of acids
- Water purification
- Removal of carbon dioxide from process gases

During the experiment work, each of the students in the group is required to keep data, graphs, and analyses. One of the students is then designated to write the group's report. The project assistant grades each student based upon the report, upon the individual reports written after each day of experiments, and upon the skills the student shows during his work.

The equipment used in these laboratories is

quite extensive, and well maintained. It is usually associated with a professor's current research or has been obtained after a research project has been completed. Equipment is also available for new projects when an old project is phased out after three or four years. Thus, the research remains open-ended, and ten-year-old equipment and projects do not exist.

By the fourth year of study, a student has chosen major and minor fields of specialization, and has a specific research aspect of the research project of a professor or graduate student. Now the student truly has access to the showcase of technology and equipment available at Delft. For example, in the reaction kinetics laboratory a student may work with any of the following equipment:

- thermal analysis (TA)
- differential thermal analysis (DTA)
- differential scanning calorimetry (DSC)
- evolved gas analysis (EGA)
- advanced impregnation apparatus
- high-temperature drying apparatus
- variety of furnaces

There is a great variety of research to choose from at Delft, and a student can review the directory that summarizes all research being conducted in chemical engineering and chemistry before he selects a professor. Some of the specific research topics available, from a recent list of thirty-two different research areas, include:

- Inhibition of crystal growth in industrial processes.
- Separation of hydrous and anhydrous calcium sulfate in the production of phosphoric acid.
- The influence of flow behavior on the separation of solids from aluminum melts.
- Automation of kinetic experiments involving the hydrogenation of carbon monoxide.
- Desalination of sea water.
- Recovery of metals from waste water.
- Removal of hydrogen sulfide from process gases.
- Production of manganese oxide for batteries.
- Pressurized fluidized bed combustion of coal.
- Process development on the hydroformylation of olefins using immobilized catalysts.

Because of Delft chemical engineering's strong emphasis on applying theory directly to research and practical industrial process problems, a Delft chemical engineer is valued highly by industry. The Delft graduate has no difficulty in adapting to "real world" chemical plants, since he has been working with small scale reactors and processes since his second year at the Delft University of Technology. □

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