CEE chemical engineering education

FALL 1968

Versatile Educator - FRANK GROVES of LSU

COHEN : Control Lab. WOODS : Design Innovations

1968 Award Lecture

SCRIVEN *surveys interfacial transport*

CAL TECH

BRUCE SAGE

BILL CORCORAN

ASEE - ChE Division Chairman

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Chemical Engineering Education

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Departments

Feature Articles

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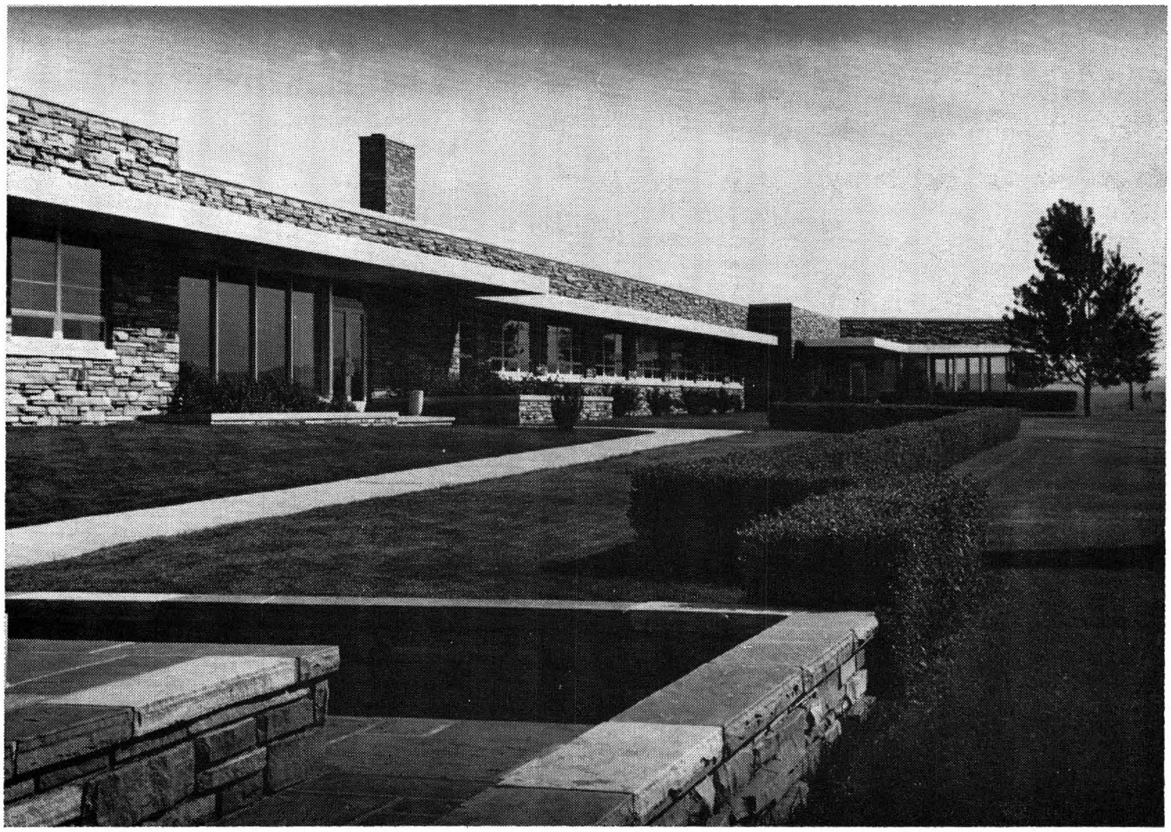
MARATHON: DYNAMIC PROGRESS



Marathon Oil Company was founded in Findlay, Ohio in 1887; however its ultramodern Denver Research Center is located at the foothills of the Rockies. The company is a producer, transporter, refiner and marketer of crude oil and petroleum products on five continents throughout the world.

The Denver Research Center was established to make discovery of new petroleum reserves more economical, to help recover a larger percentage of oil in present fields, to develop more profitable refining and chemical processes, and to develop new products.

Marathon employs more than 8,000 persons at its offices around the world including its headquarters in Findlay. There are over 300 employees at the Denver Research Center of which more than half are scientists and engineers.

CHEMICAL ENGINEERING AT MARATHON

Using engineering research to determine ways to recover more of the oil from known deposits is an important part of the work at the Research Center. It includes projects aimed at stimulating wells so they will produce more oil; in situ combustion; and fluid injection processes, such as miscible displacement, which are more efficient than conventional techniques where gas or water are used to drive oil to a production well.

Reservoir mechanics comprise another significant part of the engineering work at the Denver Research Center. The transient behavior of oil reservoirs and the flow of fluids through porous media are important phases of this work. Mathematical models, which simulate reservoir behavior, provide insight into future behavior of oil bearing reservoirs.

Chemical engineers are also engaged in the pilot plant study of existing refinery and chemical processes as well as in the evaluation and development of new processes and new chemicals. Projects are underway, for example, on petrochemical processes to make monomers and other basic components for polymers.

At Marathon's Research Center, qualifid engineers are provided with both the challenge and incentive in supplying answers to these problems. Your further inquiry is invited.

Mr. L. Miles
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AN EQUAL OPPORTUNITY EMPLOYER

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MARATHON OIL COMPANY
DENVER RESEARCH CENTER
LITTLETON, COLORADO

THE GOALS of a Chemical Engineering Department

Modern chemical engineering has developed with one root in chemistry and other roots in the engineering sciences and physics. Its trunk is a multichannel communication cable which might be termed process control and systems engineering. Its major branches consist of the macroscopic concepts of unit operations and of process equipment design. Its outer branches are developmental laboratories, pilot plants, and processing plants. Its leaves and fruits are the products and goods of our consumer economy. Without its roots, it will die; without its trunk, the leaves and fruits will not develop; and without its fruits, it has no reason for existence.

The language of chemical engineering is computer science, mathematics, and graphics. Its verification is experiment; its validation is the utility of its products; its restraints are economics and human well-being.

The identifying characteristic of chemical engineering is change: it deals with changes in state, changes in composition, changes in kind and content of energy, changes in size and aggregation, changes in biological or chemical species, and changes in appearance and quality. Since products and processes are themselves ephemeral, chemical engineering cannot lastingly or properly be defined in terms of certain products, certain processes, or certain processing methods.

As a consequence, its goals are bifold: its current major industrial goal is the economical design and operation of plants and equipment; but its academic goal is the generalization, dissemination, discovery, utilization, and extension of human knowledge in the basic sciences and concepts that comprise its roots and its trunk and branches.

A broadly oriented research and instructional program in modern chemical engineering must be cognizant of these duplicate sets of goals. It must include research in the engineering sciences such as transport and rate processes, fluid mechanics, properties of materials, and thermodynamics. It can include research in chemistry, such as work in polymers. It must include work in systems engineering, in separations processes, unit operations, and process control and economics. Finally, it can be involved in interdisciplinary areas such as bioengineering, biomedical engineering, environmental engineering (pollution), electrochemistry and energy conversion (fuel cells), and computer science and applied mathematics.

Just as the ultimate objective of the university is to serve the community of mankind, so also the goal of a department of chemical engineering must have its purpose in the betterment of human society. For, as a professional man, an engineer is not merely a technical robot who responds passively and unquestioningly to conformist pressures or to the commands of others. Instead he must be aware of, and deeply concerned with, the social and political problems of our time. He must have a high sense of values and be capable of making decisions with regard to principles and ideals derived from these, rather than from narrow self-interest or partisan group-interest. In keeping with this philosophy, a department should investigate methods of establishing communication between the "two cultures" of technology and the humanities. It should also explore programs of educational assistance to other nations.

Of great importance to the implementation of its goals is the need for adequate facilities. But, while bricks and mortar are important, what it infinitely more important is the brilliance of the experienced researcher in his indefatigable task of adding the bricks of human knowledge to the whole structure of man's intellectual development, and the skill of the dedicated teacher in the bonding of these stones with the cement of theory, generalization, and experiment.

R.W.F.

from our READERS

This interesting correspondence between Professor Lloyd Berg and Senator Lee Metcalf is a result of the publication of Professor Berg's paper, "Why a Scholarship Program in ChE" in CEE 2, 78, 1968.

Senator Metcalf's comments:

Dear Dr. Berg:

I have just read your letter and your article, an exposition of a formula A/B = C/D, which you devised to illustrate your disapproval of the amendments to the Selective Service Act which curtailed graduate student deferments.

What immediately struck me is the absence from your equation of the most basic component, the human factor, an omission that dismays and saddens me. And there is a false element, too, in the statement, "The country was on an equality binge and it was deemed politically expedient to treat PhD engineers and scientists in exactly the same manner as high school dropouts."

By no means are all of the men who have been drafted (or even a very large percentage of them) and who have served in the armed forces in Viet Nam, high school dropouts. And, by no means have graduate engineers and scientists been treated as high school dropouts. Their treatment (either because of intellectually superior backgrounds or because of good fortune or a lucky combination of several factors, often including diligence) made them, in the words of a British writer, more equal than anyone. That cannot be said of high school dropouts. Current efforts to encourage more of our youngsters to complete high school are testimony to a great need in our society—and an educational system that is still striving to meet that need.

The fact is, however, that 77.3 per cent of men drafted into the armed forces in the calendar year of 1967 had graduated from high school; some of them are numbered among the 25,000 who have been killed in Viet Nam; many are college graduates who, for one reason or another, did not seek advanced degrees in engineering or were not deferred for other reasons.

These are human beings we are talking about. All of them, no matter what their intellectual or academic attainments, face a common denominator of sacrifice which ought to make brothers of us all—and while I deplore the undeniable loss to this nation's technology, on which you have concentrated, I cannot take so parochial a view as you. I do not think of these young men as engineers, mathematicians, physicists, poets or painters. If I did, I might show a predilection to spare only poets from service in the armed forces. But I don't think that way. These young men are human beings, with the same love of life that is common to man.

For a democracy, there is really no answer except universal national service which touches all men over a given age or a random system of selection which cannot discriminate by situation in life, degree of education or other criteria, except physical or mental unfitness.

I hope that we could have some sort of system where every boy and girl in America would serve the government for at least a year. Some would go into the military; others would be chosen for the Peace Corps, Vista, Head Start or some other service program. Each of these services would be equal in regard for those who serve and each person would be able to hold his head high as one who has served his country in some important and significant endeavor. There is abundant room, in such a plan, for engineers and poets.

Finally, I guess I doubt that the human sacrifice and suffering inherent in a wartime draft of young men can be reduced to a formula.

I stated my views on the war in Viet Nam in a symposium last May at Montana State University. A copy of my remarks is enclosed.

Lee Metcalf
U.S. Senator from Montana

Berg Responds:

Dear Senator Metcalf:

Thank you for your letter of August 1 and the accompanying reprint of your speech at the MSU Viet Nam Symposium. I agreed with your speech when I heard it and am still in accord with your views. I'm sorry that you don't have an even larger influence than you do on U. S. foreign policy.

The article that I sent you was not meant to complain about the past. The U.S. draft policy up to June 30, 1968 worked pretty well with respect to scientists and engineers. It is thinking about what will happen after July 1, 1968 that gives me a sinking feeling. Prior to July 1, Selective Service had a list of critical skills and essential occupations. Engineers and scientists serving in these fields were deferred; those that didn't were subject to the draft. Effective July 1, 1968, the National Security Council abolished the whole list. Had supply finally caught up with demand? No, the Brain Drain article I sent you showed that demand was continuing to outstrip supply. Was the list unnecessary in the first place? I have no reason to believe this. The public press never brought out anything to confirm this point of view. I therefore concluded that the changes came about as a result of a policy of "fairness and equality" for all.

I agree with your suggestion about national service for all citizens but I think engineers and scientists should do it in "critical skills and essential occupations" and for far more than one year. The difficulty with any other kind of service—military duty, Peace Corps, Vista, Head Start, etc.—is that the engineers will never return for additional study. In my 25 years of college teaching, I have only encountered two who returned from military service to further their chemical engineering education.

As one of the one hundred United States Senators, you must worry more than ordinary men about the ultimate safety of the United States. From the beginning of history, nations have been playing "wipe-out" with each other. Even during our lifetime we have witnessed several examples. On September 1, 1939, Hitler launched his infamous attack on Poland. In two weeks, Poland's armies were annihilated and on September 17, Russia moved from the east. On September 18, Russian and German troops met at Brest Litovsk and Poland ceased to exist.

Captured Nazi documents submitted at the Nuremberg trials showed that Germany planned to wipe out completely all of Russia east of the Urals. As the German army conquered Russia, the peasants were to be left on their farms and permitted to keep just enough food to live on. All the rest would go to Germany. Absolutely no provision was made for the feeding of the rest of the Russian people in the conquered territory. They would just starve to death.

At the present time, ask any Nasserite, Jordanian or Syrian what are his country's plans for Israel. They will tell you frankly that it is their national policy to push Israel into the sea.

During our lifetime too, you and I have seen a number of examples of politicians paying little heed to their nation's scientific and technical capability until they were in desperate straits and then calling for the technically impossible. On May 10, 1940, the battle of France began. The French people had been assured for twenty years that their Maginot Line was the finest defensive system in the world and that the country was in no danger. Actually French technology had progressed very little since World War I. Five weeks later with the Nazis storming the gates of Paris, Premier Paul Reynaud issued his plaintive call to President Roosevelt for "clouds of airplanes."

Fortunately for civilization, it wasn't only the "good guys" that have let their technology slide. In 1942, German submarines sank 6,250,000 tons of Allied shipping, a tonnage far beyond the capability of western shipyards to replace. Had this rate continued, Britain would surely have been brought down. But in 1943 the U-boat losses zoomed and Allied ship sinkings miraculously dropped. Why? Because a few young American and British engineers applying new knowledge of radiant heat transfer had developed radar. This enabled Allied aircraft to locate and destroy the U-boats long before they got close to the convoys. Admiral Doenitz at first suspected treason but when he finally learned that it was radar, he withdrew the U-boat fleet. In late summer however, Hitler insisted that German bravery could overcome American technology and ordered the fleet to sea again. In the last four months of 1943, the Nazis lost sixty-four submarines while sinking only sixty-seven Allied vessels. This loss ratio spelled doom for the U-boat warfare and settled the Battle of the Atlantic.

By the spring of 1945, the Third Reich was in its death throes. Both the eastern and western borders had been crossed by the Allies and the German cities were mere rubble heaps. About 8-million Germans had been killed, virtually an entire generation. What was the word from Hitler under those circumstances? His scientists and technologists led by Werner Von Braun, were going to save Germany yet with their V-1 flying bombs and V-2 rockets.

Frankly, Senator Metcalf, I am concerned that the policies established last July 1 will cause the United States to lose its technological lead. That is a situation that cannot be quickly remedied. It takes a minimum of eight years from the time we interest a high school student in science or engineering until he is awarded the PhD. No crash program, no large infusion of money can speed up this process. Can we gamble with our national safety? In this nation of 200-million people, does the continued training of a few thousand engineers and scientists in critical skills and essential occupations really upset greatly the general policy of fairness to all?

May I have your permission to publish your letter of August 1 and this reply? LLOYD BERG,
Montana State University

The Senator has the last word:

Dear Dr. Berg:

I have long talked about the need for scientists and engineers in the National Defense Education Act. I deplore the fact that $6 billion reduction of the budget has cut out essential research and development programs, of the National Institutes of Health and the National Science Foundation and pure research and development as far as the military is concerned.

Experience has shown that a statement that engineers will never return for additional study is not an accurate one. The GI bill and now the new bill for Korean and Viet Nam veterans has attracted thousands of boys back to advanced studies, including the engineering field.

I don't want to enter into an extended debate with you on the question; I feel that your statement in the article about an "equality binge" is unfortunate and hope that you will agree that essential equality here is not a sacrifice of life itself and if we are going to demand that sacrifice of young men we must demand it of them whether they come from homes where their parents ar rich and affluent or whether they come from homes where they have not had either the educational or cultural opportunities to attain the status of a graduate student in science or mathematics. We need more equality, not less.

Yes, you have my permission to publish my letter of 1 August, if it is published in full together with this letter.

LEE METCALF
U.S. Senator from Montana

Summer Issue

Editor:

From cover to cover, I read it! I don't do that for very many publications, but your Summer 1968 issue of Chemical Engineering Education was outstanding. Please accept my congratulations.

Joseph J. Martin
University of Michigan

Editor:

That Summer issue of CEE! A splendid job. Everything in it is interesting and valuable.

Olaf Hougen has countless admirers who will enjoy reading about him.

Keep up the good work.

M. C. MOLSTAD
University of Pennsylvania

(Letters continued on page 160.)

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University of Colorado
University of Iowa
University of Oklahoma.
University of Pittsburg

FLOW and TRANSFER at FLUID INTERFACES*
Part I - Lessons from Research

L. E. SCRIVEN
University of Minnesota
Minneapolis, Minn.

Chemical engineers cannot escape dealing with mass and heat transfer across fluid interface that are in more or less chaotic motion, chaos that goes under the name of turbulence. There is little need to emphasize in this magazine why a thorough understanding of flow and transfer at fluid interfaces is an important research goal—and ultimately a standard tool in the kit of practicing engineers.

Put broadly, the problem I wish to discuss is that of transfer in chaotic or turbulent flow systems, particularly those in which turbulence is generated at some distance from the interface but comes to bombard it, so to speak. Underlying this broad problem there is an important basic question: What are the effects of convective movements on otherwise diffusive transport, particularly in the neighborhood of fluid interfaces?

Fluid interfaces are mobile and can move and deform in ways that solid boundaries cannot. It is important to bear this in mind, because solid boundaries are so much simpler and better studied that they are the underpinning for most of one's intuition in this area. I think it instructive to look at the ways in which the chemical engineering profession has tried to model flow and transfer at fluid interfaces in the past. For simplicity, let us disregard such complications as the transfer resistance of the second phase, diffusion-induced convection, inhomogeneous properties, interfacial-tension gradients, chemical reaction effects, and so on. We can then identify four or five stages in the development of transfer models.

STAGE ONE: NO FLUID MECHANICS

The earliest working model can be traced back to Newton's empirical law of cooling, in essence a one-parameter representation of convective diffusion near a solid surface. The same tactic emerged between 1895 and 1905 in the idea of a diffusion layer or stagnant film adjacent to a soluble solid in contact with stirred solvent. The principals were all chemists, the Americans Noyes and Whitney, Russian Shchukarev, and German Nernst. In 1912 Irving Langmuir, having completed his PhD with Nernst and quit Stevens Institute of Technology to join General Electric, reported on his studies of heat transfer from lamp filaments. Citing the high viscosity and high thermal conductivity of gases at filament temperatures of 2200°K and higher, Langmuir stated that the loss of heat by free convection—and even forced convection—takes place exactly as if there were a film of stationary gas around the filament, through which the heat is carried entirely by conduction. This idea of a conduction or diffusion film was picked up by W. K. Lewis and his chemical engineering colleagues at MIT, who elaborated it into the familiar "two-film theory" of transfer across *fluid* interfaces. But in doing so they obscured the hot and hypothetical character of Langmuir's stationary film: Lewis and Whitman (1924) actually wrote of surface layers of liquid "practically free of mixing by convection," which could be interpreted as merely laminar flow, probably rectilinear flow, possibly plug flow and effectively stagnant films. Successive editions of the standard textbook by Walker, Lewis, and McAdams appear to have spread the stagnant-film picture along with the series-resistance concept. Chemical engineers focussed on measurement and correlation of "film thicknesses" or "transfer coefficients."

The physical picture from this first stage consists of separate diffusion resistances characterized by lumped parameters as in elementary electrical circuits. It requires only simple algebra, although an ordinary differential equation is in the background. Rather than fixed potential or fixed flux at phase boundaries it in effect rests on the next simplest boundary condition, a linear relation between flux and potential involving only a single empirical parameter to describe whatever combination of convection and diffusion exists. There is no evidence of familiarity with relevant concepts from classical inviscid hydrodynamics, much less from the viscous flow theory that was available in the first decades of the century.

*Presented at the Annual meeting of ASEE, June 18, 1968 as the opening part of the ChE Division Distinguished Lecture, sponsored by the 3M Company. The second part will be published in a later issue.

What are the effects of convective movement on otherwise diffusive transport, particularly in the neighborhood of fluid interfaces?

STAGE TWO: RECTILINEAR FLOW IDEAS

Higbie in his 1934 thesis and well-known 1935 paper recognized that when gas and liquid are brought together there must first of all be penetration of the liquid by the dissolving gas, and that this sort of thing happens repeatedly in bubbler absorbers and packed towers, any bit of interface between gas and liquid having a limited life or time of exposure. Much the same idea had been put forward independently by the Dutch physiologists Dirken and Mook in 1930, who were concerned with gas exchange with blood yet judged it worthwhile to study basic aspects of absorption. Like Higbie they attempted to demonstrate their idea experimentally. Higbie knew and understood the physical chemical literature on diffusion. On the fluid mechanical side he had some appreciation of turbulent flow, for example in Miyagi's experiments; but he adopted the Lewis-and-Whitman picture of a film of liquid at the interface and regarded it as being in streamline flow, by which he evidently meant rectilinear, plug-like motion. Vyazovov in 1940 and Pigford independently in 1941 applied "penetration theory" to absorption into falling liquid films in rectilinear flow with semi-parabolic velocity profiles—taking a convective diffusion effect into explicit account for the first time. Such endeavors were familiar from the heat transfer literature, however, for example in Leveque's 1928 analysis which was featured in T. B. Drew's wonderfully prescient paper a few years later in the Transactions of the AIChE. Mass transfer into rectilinear flows is still an active topic, as evidenced by researches by Kramers and Kreyger (1956), Beek and Bakker (1967), Byers and King (1967), and one of my coworkers, Majoch.

Historically in the second stage the model consisted of highly idealized flow parallel to the fluid interface, flow that somehow is regularly interrupted after an ill-defined exposure time, and can then be re-established. Analysis of transfer involved a comparatively simple partial differential equation more familiar in the theory of heat conduction, where many relevant problems had already been solved. By the mid-40's the powerful Laplace transform technique was an effective tool in the hands of a few chemical engineers. Fluid mechanical concepts were not, but Prandtl's boundary layer notions were being applied elsewhere to heat transfer between solids and fluids.

STAGE THREE: TURBULENT DISTRIBUTION FUNCTIONS

This stage might have opened with chemical engineering notice of the 1932 Royal Society paper by Fage and Townend reporting microscope observations of suspended particles in "semi-turbulent" motion 0.001 inch from a *solid* wall, well within a "laminar" or viscous sublayer thirty times thicker. Or of the summary and discussion of those observations in Goldstein's "Modern Developments in Fluid Dynamics," the beacon work that appeared in 1938. Or of the 1949 paper by Kishinevskii and Pamfilov, in which hypotheses of laminar sublayers and films near fluid interfaces in well-agitated systems were rejected in favor of a picture of turbulence *continuously* renewing interface and transferring solute by convection alone. The investigators from Kishinev employed very fuzzy algebra and integral calculus and did not hit upon the convincing arguments for their heretical contention that the mass transfer coefficient could be independent of molecular diffusivity; worse still at that time, they wrote in Russian. Two years later and independently, Danckwerts too rejected the by then conventional misconception of a "stagnant" film; he held it likely that "turbulence" can extend to a fluid interface, erasing all resemblance to laminar boundary layer flow there; and he set about showing that working formulas derived from the stagnant-film hypothesis can be derived equally well from more palatable hypotheses. In his well-known surface renewal theory Danckwerts related the rate of absorption by penetration in Higbie's model, to an empirical parameter s characterizing the rate and reflecting the statistics of surface renewal—on grounds that an undefined "scale of turbulence" is so much greater than the "depth of penetration" that "relative motion of liquid at different levels close beneath the surface may be disregarded" (as I shall bring out later, this presumption can be quite inaccurate). The basic contribution was the application of statistical ideas to the picture of surface renewal, or replacement, as a stochastic process powered by an underlying turbulent field. Subsequently Danckwerts, Hanratty, Davidson, Perlmutter, King, Koppel and others have put forward various distribution functions of surface age, exposure time, or residence time. Andrew, Dobbins, Toor and Marchello, and Harriott have proposed modifications in Higbie's original penetration model, one reason being to bridge the gap between the old film formulas and the surface-renewal formulas for the dependence of mass transfer coefficient on molecular diffusivity. The same reason has led still others to offer rankly empirical correlating formulas that warrant no further comment.

The dominant physical picture in the third stage is of locally intermittent yet grossly steady "surface renewal" by distinct "eddies" the arrivals of which follow various statistics that are supposed to represent the essence of turbulence. There is evidence here of growing awareness of fluid mechanics and of considerable mastery of the mathematics of age and residence-time distributions, the latter a topic that became increasingly fashionable in chemical engineering analysis during the fifties.

STAGE TWO *bis*: CURVILINEAR FLOW WORK

Simultaneously with the preceding stage there emerged, from analyses of simple laboratory absorbers designed for basic studies, a lot of information on the effect of curvilinear laminar convection on diffusion. This information can be used to construct significant generalizations of Higbie's original penetration model (as I shall discuss later). First came a rather crude analysis by Lynn, Straatemeier, and Kramers in 1955 of absorption into the nonuniform film flow over the surface of a sphere. Davidson and Cullen then treated the same problem more satisfyingly with the convective diffusion equation. In the same period I tackled end effects in wetted-wall columns and laminar liquid jets, and a year or two later the papers by Scriven and Pigford appeared, emphasizing the strong effect of the velocity component *normal* to an accelerating interface and presenting accurate general formulas for situations in which the scale of relative tangential motion is much greater than the "depth of penetration." The same results were independently rederived by Angelo, Lightfoot, and Howard in 1966 and presented with emphasis on the surface dilatation, divergence, or "stretch" that accom-

The dominant physical picture in the third stage is of locally intermittent yet grossly steady "surface renewal" by distinct "eddies" the arrivals of which follow various statistics that are supposed to represent the essence of turbulence.

panies convective motion normal to the interface. Models of flow and transfer in boundary layers at fluid interfaces in nearly rectilinear flows have been treated by Potter (1957), Beek and Bakker (1961), and notably Goren (1966). Others have studied the simultaneous diffusion and convection around a growing bubble. The most significant curvilinear flow work (in my estimation, and for reasons to be discussed) is my former co-worker W. C. Chan's exact solutions of the problem of transient convective diffusion in irrotational stagnation flow, which formed part of his 1964 thesis. Very recently Majoch, exploiting a 1967 observation by Romanians Ruckenstein and Berbente, has added a solution for a case of rotational stagnation flow as well.

These developments reflect increasing mastery of the relevant fluid mechanics, expanding experience with the convective diffusion equation, and growing proficiency in the similarity and approximate methods for solving it.

STAGE FOUR: TURBULENCE CONCEPTS AND MODEL FLOWS

Levich, as described in the translation of the second edition of his "Physicochemical Hydrodynamics," was the first to apply Prandtl's mixing length scheme of dimensional analysis—for that is all it is—to absorption at a fluid interface buffeted by eddies generated at depth. His attempt spawned others by Ruckenstein and by C. J. King, the latter placing the greatest reliance on the controversial notion of a turbulent eddy diffusivity, the origins and justifications of which lie in the rather different process of turbulent transfer across mean streamlines that are nearly rectilinear, as in duct, boundary-layer, and jet flows. More fundamental turbulence theory is in short supply, and what is available has been classified by the authority Townsend into wall turbulence, free turbulence, and convective turbulence. Conspicuous in its absence is a corpus of what I would call interfacial turbulence had not that term been pre-empted; "free boundary turbulence" must do. Free boundary turbulence is convective chaos only

partially constrained by the presence of an interface that allows great freedom of tangential movement, and restricted though appreciable freedom of normal movement.—and which is capable dramatic conversions of larger scale into smaller scale motions.

Danckwerts remarked in his 1951 surface-renewal paper that "A complete development of the subject would require further discussion of the relation of s [the renewal rate, or reciprocal of mean exposure time] to the hydrodynamics and geometry of the system." Only very recently have the first tentative steps been taken in this direction, for example by Shulman and Mellish in observing flow patterns in packed towers (1967), Fortescue and Pearson using turbulent channel flows (1967), and Ting and Davies with turbulent liquid jets (1967). Efforts are also afoot to relate to turbulence parameters not only the constants in distribution functions, but also their functional forms and the local flow-and-transfer models—Chan's microflow elements—which are regarded as being distributed. In still unpublished work my former associates Spriggs and Grgurich and I have toyed with a fascinating experimental model of a turbulent "eddy" (of which more later). Two years ago Boyd, Muenz, and Marchello reported experiments on the effect of simple progressive surface wave motion on gas absorption; unhappily any effect was overridden by extraneous large-scale convective motion. The same complication intervened in the more recent investigation of absorption into standing surface waves by Mani and Goren (as it had in a cruder attempt under my supervision in 1964, and as it probably did in the experiments of Bretsznajder and Pasiuk in Poland a couple years earlier). Attempts at analyzing the effects of surface waves on transfer in seemingly accessible special cases have been made by Chan (1964), Bentwich (1966), E. E. O'Brien, (1967), and my Brazilian associate Vieira.

In this current stage of development turbulence concepts and model flows have not yet been united. Attackers on both fronts are, or ought to be, armed with the same increasing mastery of fluid mechanics that I pointed out earlier. Unfortunately the basic fluid mechanical information that is really needed is simply not available, and one should ask whether chemical engineers are to continue messing around with what little is available, or are they to go after some needed "engineering science" themselves?

Dr. L. E. Scriven is professor of chemical engineering at the University of Minnesota. He was educated at University of California (Berkeley) and University of Delaware (PhD '56). He has received many awards for outstanding contributions to research and teaching in engineering. His research interests include fluid mechanics, some associated mathematical methods and the application of engineering to biology.

STAGE FIVE: PENDING DEVELOPMENTS

For reasons some of which should become clearer as I proceed, I believe the major areas of research on flow and transfer at fluid interfaces in the near future will be—or should be!—the following: 1. Observations of turbulent interfaces by high-speed, high-magnification photography and, later on, measurements of correlation and intermittency factors within the fluids. 2. Theory of convective diffusion fields, particularly velocity fields which admit useful exact solutions or typify periodic and almost periodic motions. 3. Comparative studies of the sensitivity of final working formulas to the details of both model microflow elements and the distribution functions they might follow. 4: Theory of free-boundary turbulence, transversely isotropic and unidirectionally inhomogeneous.

Actually I set out above not to prognosticate, but to examine the ways in which chemical engineers have thought about transfer between fluid phases. It is obvious that the successive stages in their thinking have depended directly on the current levels of physical *and* mathematical sophistication. The sophistication must be possessed both by the innovator, who has to express original physical insight in mathematical language if it is to support engineering calculations, *and* by the user, who must grasp that language and should understand the underlying physical insight. We can see failures on both counts in the histories of the (stagnant!) film, penetration, and renewal theories, which have frequently been less than perfectly understood—even among chemical engineering textbook writers.

Though I haven't emphasized the fact in the foregoing review, I should point out that there is a lasting value of *simplicity* in a concept, a model, or a theory. The simplicity of something that has served us well in the past is a strong driving force for rationalizing it anew after we have become aware of its considerable limitations and perhaps temporarily rejected it in the light of newly won sophistication. An obvious example can be seen in the multitude of interpretations the mass transfer coefficient has earned since its filmy start. On the other hand, there is real danger in too easy or too attractive a model. The formalism of the film theory apparently was so elementary as to have deceived students and mature engineers alike into investigating basic mechanisms no farther during a couple of decades of Middle Ages. And a different example: Fascination with distribution functions and the like seems to have been so great as to obscure the distinction between the statistics obeyed by model elements and the working of an individual element, and to inhibit inquiry into the latter during a decade or more of the Modern Age.

POSTSCRIPT

This seems an appropriate juncture, before returning to flow and transfer, to express my opinion that as engineers learn new science, however esoteric, and acquire mathematical skill, however abstract, their tradition and habit of practicality will produce engineering applications. The applications may come directly in invention, design, and operation or less directly—and often more profoundly—in concepts and patterns of thought that pass into what we call "physical intuition" and "engineering judgment."

Yesterday's dimly viewed science and incomprehensible mathematics are today's engineering research areas and tomorrow's engineering practice—and undergraduate course contents. Of course the undergraduate student must learn what engineering is about, and he should see in his professors a broad selection of engineering experience and outlook. But he should also have the opportunity of acquiring a truly liberal education, and this requires continually up-to-date scientific and technological competence within the engineering faculty. Maintaining this kind of competence takes research and substantial numbers of professors of the sort called engineering scientists—or, pejoratively, pseudoscientists. In my experience it is greatly aided by the presence of true scientists on the engineering faculty. True or false, these are persons whose participation signals the decline and fall of real engineering to a certain type of mind. Yet, how much might earlier competence in the areas of fluid mechanics and applied mathematics I mentioned have benefitted my present subject and chemical engineering in general! Suppose the young metallurgical engineer with a PhD in physical chemistry, Irving Langmuir, had joined the engineers and entrepreneurs at a leading university instead of the chemistry professors at Stevens! Why weren't there other young Langmuirs, more Drews and Higbies, researchers who scouted in the literature of physiology and Soviet applied science, critics to point out that not all films are 2300 degrees hot and stagnant? . . .

PROCESS DYNAMICS AND CONTROL

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Dr. William C. Cohen is Associate Professor of Chemical Engineering at the University of Pennsylvania. He has a BChE degree from Pratt Institute and MSE and PhD degrees from Princeton University. In 1966 Dr. Cohen received the Lindback Foundation award for distinguished teaching.

Dr. Cohen is interested in making laboratory work more meaningful and effective in engineering education and in the inclusion of laboratory studies within lecture courses. His research interests center on the dynamics, control and optimization of process systems.

Process dynamics and automatic control theory uses truly wonderful but abstract mathematical relationships. It is important therefore that the students get the opportunity to apply this theory for reinforcement, appreciation, and motivation as well as to develop some intuitive feel for system dynamics and control. To this end a number of "case" and laboratory studies have been developed and used to aid in the teaching of process dynamics and automatic control.

The reader will note that the "case" studies described here are not taken from engineering practice but have been fabricated to strike a happy compromise between realism and complexity. In some ways they are like a long homework problem but to the extent that they involve laboratory or computer experimentation as well as latitude in how the student may approach them, they differ significantly in their effectiveness.

Study 665-11, Control of a Shell and Tube Heat Exchanger is used in conjunction with analog computer equipment. It is used as a culminating study of a one term undergraduate engineering science course or as an initial study in a graduate level chemical engineering course whose prerequisite is an introductory feedback control course.

The first part of this study involves process identification from experimental test data. The process is simulated on part of an analog computer connected to a graphical panel which depicts the process and to which the students may direct their attention with minimal knowledge of analog computation. Through the use of the remainder of the analog equipment or other test equipment as desired, the students may probe the simulated process. Their goal is to determine the governing differential equations or transfer function of the process.

There are two variations to this procedure worth mentioning and which may better fit the purposes and facilities of others. The first is to present the student with the results of a dynamic test. The second variation is not to use a simulated process at all but to use a real piece of process equipment such as the double pipe heat exchanger found in most unit operations laboratories.

The next part of the studies present the need to develop a theoretical dynamic model for a thermocouple in a protective sheath which is a part of the process system not included in the experimental testing done previously.

Now with the differential equations or transfer function of the complete process system determined, the next part of these studies involves the design of a proportional-integral controller for it. On a plot that uses the loop gain as abscissa and reset rate as ordinate they locate the stability locus, their control system designs, and the controller settings estimated by the Zeigler-Nichols and Cohen and Coon correlations.

In the next part of the studies the students observe the operation of the complete controlled system on an analog computer simulation. They can check out the stability locus and then observe the performance of their control system designs. They then search for optimum controller settings which minimize the integral of absolute error. They will notice different performance in response to set point changes or process disturbances. And they will have to evaluate the stated specifications on system performance.

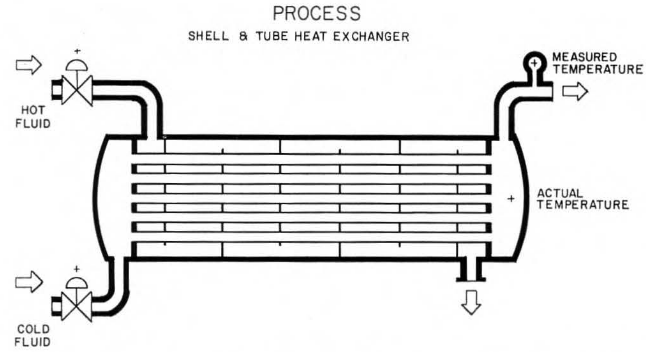
Again depending on purposes and facilities, variations are possible such as digital computer simulation of the system or observation and optimum search on a laboratory process unit directly.

The final aspect of these studies is to report these results. I have found it most effective to use student groups of two with different groups doing different studies. Each student will spend 12-15 hours on the study which can be compensated for by weighting the studies as a two hour examination and/or waiving some lecture time.

Study 665-15, Control of a Liquid Level System is a laboratory study whose purpose is to acquaint the students with transducers, pneumatic diaphragm valves, industrial recorders, etc. They nicely show how the initial steady state conditions, which are submerged in the theory, rise to the surface. In this study we again use our analog computer but this time as the real time controller in the system. The use of the computer has the advantage that the student has great flexibility in choosing control modes. Other advantages are that we do not have to buy additional controller equipment and the student is introduced to a true computer control system.

By confining the study to empirically obtaining the best control of the liquid level in the tank, we find that the students can complete the study in a four hour period exclusive of the report. In this system the dynamics are very nearly first order due to the slow first order response of the level in the tank to inlet flow and excellent results are obtained with an on-off control mode. The students do not generally recognize this in advance and usually first try a proportional-integral controller with low gain. They are surprised at the poor performance and finally arrive at a high gain proportional or an on-off control mode.

Either because of the fun of being challenged by a real (or simulated) process or because of the generous weighting given to the studies, they have been received with enthusiasm by students at both the undergraduate and graduate level. I have also used these studies successfully with graduate engineers and scientists in a continuing education course. One of these students once remarked that for him, "doing the study was worth the price of admission."



Case Study 665-11. Shell and Tube Heat Exchanger

The P. Tomaine Soup and Food Company has decided to increase production rate for their Backwoods Bean Soup by preheating the stock before it is placed in the cooking vessel. They own one of the few continuous soup cookers in existence. A preheat temperature of 140°F is desired. Too high a temperature results in an off-flavor while too low a temperature lowers the production rate and upsets the cooking process. Quality control decides that ±3°F is permissible.

P. Tomaine is active in the business and indeed was responsible for the process development work on Backwoods Bean Soup. He recalls the heat exchanger shown in the accompanying figure and reasons manual control would be ineffective because of the varying stock inlet temperature, and the varying stock consistency which alters the heat transfer characteristics. He decides to consider automatic control of stock temperature by manipulation of stock flow rate through the exchanger, and sets about to assess the dynamic characteristics by a step response test. The stock inlet valve is of the pneumatic diaphragm type with a 3-15 psi range, air pressure to open. Tomaine installs a bare 30 gage copper-constantan thermocouple to measure the pre-heat temperature because of its almost instantaneous response although he knows Backwood Bean Stock will dissolve it in about 14 hours. At a time when the plant disturbance appears minimal he records the data in Table 1.

a. What transfer function would Tomaine obtain upon analysis of his data?
b. If instead of performing a transient response test he had taken frequency response data, what would the magnitude ratio and phase angle plots be?

A simulation of the heat exchanger in terms of perturbations about an initial steady state has been set up for you on the analog computer. The steady state corresponds to 10 psi on the diaphragm valve giving a soup stock temperature of 140°F at a stock flow rate of 980 gallons per day. One computer second equals 1 problem minute and 1 computer volt is equivalent to a change of 1 psi air pressure on the diaphragm valve in the cold water line. Although you can obtain the dynamic characteristics of the

Table 1.—Response Data for Heat Exchanger.

Temperature °F	Time, sec. (Stopwatch)	Notes
140	4:40 P.M.	Valve at 10 psi
140	0	Valve suddenly changed to 8 psi. Stopwatch started
140.07	3	
140.27	6	
----------	12	Dropped notebook.
142.0	18	
143.25	24	
144.64	30	
146.11	36	
----------	42	Telephone
149.1	48	
151.99	60	
162.43	120	
167.09	180	
168.91	240	
169.60	300	
170.00	4:50 P.M.	Returned process to 10 psi.

process by interpretation of the computer wiring, the object of this study is to treat the simulation as the real world and you will obtain greater benefit by not analyzing the computer wiring for the process.

a, b. Now, make any experimental tests you want and determine the transfer function of the process. Report this result before proceeding further.

Tomaine now decides to assess the transfer function for a rugged thermocouple imbedded in a sheath (well) which will not dissolve in the soup. They have successfully used a 1 inch O.D. capped steel cylinder about 6 inches long and 1/16 inch thick. Tomaine estimates the overall heat transfer coefficient from stock to thermocouple location in the well to be $U = 183.4$ Btu/hr-ft^2 — °F.

c. If he considers the well to be at a uniform temperature, what transfer function does he derive for the thermocouple assembly?

Tomain now feels he is in position to consider applying a proportional plus integral controller to the process, i.e.

$$m(t) = K_c\,[e(t) + R\int e(t)dt]$$

where

$K_c = 100/(\text{Prop. Band})$

$R =$ Reset rate, repeats/min

and

$$\frac{M}{E}(s) = K_c\,(1 + \frac{R}{s})$$

d. With total loop gain ($K = K_cK_PK_B$) as abscissa and reset rate as ordinate plot the locus dividing regions of closed loop stability and instability.

e. On this same plot locate the control systems designed by gain and phase margin considerations and also by root locus techniques. Also locate Zeigler-Nichols and Cohen-Coon predictions.

f. Does Tomaine need the integral mode? Is derivative action needed? Reassess the problem definition.

g. You are invited to test your calculations by working with an analog simulation of the Backwood Bean Soup heat exchanger. First check a few controller settings on the locus separating stable and unstable regions. Notice that the simulation has provision for calculating the integral of absolute error, IAE, where

$$IAE = \int_0^\infty |\,e(t)\,|\,dt$$

Apply step changes to the set point of the process and obtain a gain, reset rate pair which minimizes IAE/S where S is the size of the step applied. As you do this determine the values of IAE/S for the control systems designed in part e. Add all this information to your K,R plot.

h. It turns out Mrs. Tomaine controls the company's funds and because of their fight last night he requests you to present the recommendations to the plant improvement committee of which she is chairman. Take no more than 20 minutes and use visual aids to help you present your conclusions.

Case Study 665-15. Liquid Level Control System

The objective of this experiment is to control, through appropriate transduction, liquid level in a continuous flow tank, using analog computer elements to simulate an automatic feedback controller. Specifically, this control will be achieved by manipulation of the flow rate of incoming liquid. A second objective is to introduce the student to some of the hardware used in real control systems.

The process system is located in the Chemical Engineering laboratory, and the essential parts are shown in Fig. 1 and described as follows.

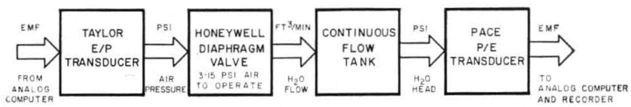


Fig. 1—Liquid Level Control System.

1. TAYLOR Electropneumatic Transducer, Model 701T, converts emf to air pressure. See company literature for specifications (voltage range, calibration, etc.).
2. HONEYWELL, ¾ in. diaphragm valve, 3-15 psi, air to open. Note that upstream water pressure should be maintained time invariant during the experiment.
3. The tank used is a cylinder, 6 in. in diameter, and approximately 24 in. high. The tank outlet to be used is a ½ in. diameter, 24 in. long pipe.
4. PACE pressure to voltage transducer and readout, model K, provides a voltage signal proportional to differential pressure on its diaphragm. See company literature for specifications (voltages produced, etc.).

The control system and peripheral equipment to be utilized are as follows:

1. PHILBRICK, Model 6009, operational amplifier bank (10 amplifiers), with power supply, black box feedback networks, etc. This can not be used to drive TAYLOR E/P transducer.
2. PHILBRICK, Model UPA-2, single operational amplifier must be used as the final amplifier in the con-

troller scheme, in order that it may drive the TAYLOR E/P transducer with up to 5 ma current. **To protect transducer use a voltage** limiter network, 0 to 12 volts.

3. Voltmeter for pot settings, amplifier balancing, etc.
4. One bank of 5 potentiometers.
5. For recording the output of the PACE transducer and the output of the controller a LEEDS & NORTHRUP Speedomax H will be used. Literature on this recorder will be found in "Readout" volume. To protect this recorder use 0.01 input attenuation external to recorder.

At this point you should compare the actual equipment with the information supplied.

The study involves your operation of the equipment to obtain the following information.

1. Obtain the dynamic characteristics of the process system on-line by any technique you wish to use. Do you feel that it is necessary to study the static characteristics of each individual component of the process system? How about the dynamic characteristics?
2. Compare the results above with a theoretical analysis of the liquid level dynamics of the tank together with any data or estimates of the dynamic characteristics of the other apparatus. Discuss.
3. From the dynamic characteristics, estimate the control needs and controller settings for liquid level control. Consider also the rapid estimations in the following references:
   a. "Zeigler - Nichols Method" in Eckman, Automatic Process Control, Wiley, 1958, p. 114-121.
   b. Van der Grinten, "Determining Plant Controllability" **Control Engineering**, Oct. 1963, p. 87; and "Finding Optimum Controller Settings," Dec. 1963, p. 51.
4. Now place the tank under liquid level control and compare control performance for a step change of 3.5 inches in liquid level.

LETTERS continued from page 149.

Editor:

I was very interested in the article by Sliepcevich and Hashemi (Irreversible Thermodynamics, CEE 2, 109-112, 1968) because it resembles a similar derivation which I evolved while teaching our undergraduate Linear Systems course here at Dartmouth. Although the methodology of this course is derived mostly from the fields of Electrical and Mechanical Engineering, I believe that the fundamental concepts are most happily and rigorously developed from thermodynamics.

My derivation differs from that by Sliepcevich and Hashemi in several aspects and I suggest that mine is both more correct conceptually and more useful in practice.

Rather than using the idea of "lost work," I started from the "rate of entropy generation per unit volume," $\dot{s}$, which was then related to the mass and energy fluxes, $\dot{M}$ and $\dot{E}$, and to the gradients of Planck potential α and inverse temperature β (Tribus, "Thermostatics and Thermodynamics," D. Van Nostrand). In a one-dimensional system we have

$$\dot{s} = \dot{M}\frac{d\alpha}{dx} + \dot{E}\frac{d\beta}{dx} \qquad (1)$$

Assuming that $\dot{s}$ is a fundamental thermo*dynamic* property which is a function of $\dot{M}$ and $\dot{E}$ we have

$$\dot{s} = \dot{s}\,(\dot{M}, \dot{E}) \qquad (2)$$

whence $\dot{s}$ is an exact differential in $\dot{M}$ and $\dot{E}$.

Following methods akin to those of Sliepcevich and Hashemi we have

$$\frac{d\alpha}{dx} = \frac{1}{2}\left(\frac{\partial\dot{s}}{\partial\dot{M}}\right)_{\dot{E}} \quad \text{and} \quad \frac{d\beta}{dx} = \frac{1}{2}\left(\frac{\partial\dot{s}}{\partial\dot{E}}\right)_{\dot{M}}$$

and hence

$$\left(\frac{\partial\frac{d\alpha}{dx}}{\partial\dot{E}}\right)_{\dot{M}} = \left(\frac{\partial\frac{d\beta}{dx}}{\partial\dot{M}}\right)_{\dot{E}} = L_{12} = L_{21}$$

where L_{12} and L_{21} are the transport coefficients in the equations

$$\frac{d\beta}{dx} = L_{11}\dot{E} + L_{12}\dot{M}$$

$$\frac{d\alpha}{dx} = L_{21}\dot{E} + L_{22}\dot{M}$$

The reciprocal relationships are obtained in a similar way by starting from the assumption

$$\dot{s} = \dot{s}\left(\frac{d\alpha}{dx}, \frac{d\beta}{dx}\right)$$

The results are easily extended to three-dimensions.

The rate of entropy generation per unit volume seems to me to be a very basic conceptual quantity. If ds is the entropy generated in a volume (dx dy dz) in time dt, we have

$$\dot{s} = \frac{ds}{dx\,dy\,dz\,dt}$$

Therefore $\dot{s}$ represents the entropy density in a four-dimensional space-time continuum. From the information theory viewpoint $\dot{s}$ is a measure of our knowledge (or uncertainty) about an element of a space-time universe. There are few more fundamental concepts than that!

I also prefer the simplicity and symmetry of my formulation which can be extended to any number of extensive (conserved) properties and their conjugate intensive (potential) variables.

There remains the question of just why $\dot{s}$ should be a homogeneous function of the second degree in the fluxes or potentials. Is there any primitive reason for this?

GRAHAM B. WALLIS
Dartmouth College

ChE classroom

INNOVATIONS IN A PROCESS DESIGN AND DEVELOPMENT COURSE

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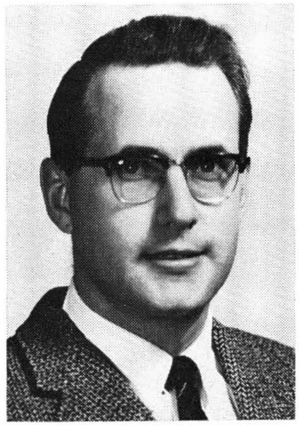
To prepare a student to make decisions based on a financial criterion, a senior course is given that introduces the student to the structure of a process or plant and to cost estimation techniques and methods of comparing the financial attractiveness of proposals. The morphology of design or of plant operation decisions, the ability to handle uncertainty and methods of optimization are introduced. Then the principles are applied to design problems and to plant operation.

The innovations in the course are the development of an approach to help the students be creative, i.e., generate alternatives, through functional analysis of processes combined with in-plant lectures. Secondly, emphasis is placed on setting-up economic balance equations, and an approach is suggested for balancing calculational time with the accuracy expected. Computer-aided optimization work is done on the models made for the simulation of a sulphuric acid plant. Finally trouble-shooting problems are uniquely used as case studies to illustrate the strategy of tackling problems, and the value of time.



Dr. D. R. Woods is an associate professor of chemical engineering at McMaster University. He was educated at Queen's University (BS) and the University of Wisconsin (MS and PhD). Professor Woods teaches courses in information management and in process design and development. His research interests are in the field of mechanical separation of particulate systems and in particular on methods of separating emulsions.

Two media are used to convey senior level design experience at McMaster: a four-credit semester lecture course to illustrate the fundamentals and a four-credit project laboratory that has no lectures. This paper describes some experience from teaching the lecture course. First a sketch of the course content and emphasis is presented; then some attempted innovations are described. The project laboratory is described elsewhere.[1]

COURSE CONTENT

The course is divided into three sections: understanding the background of processes and learning about cost estimation, developing the general principles of devising economic balances and of optimization, and applying the principles to the industrial problems of design and operational efficiency.

Understanding the Background. Students are used to thinking about commodity balances; i.e., they meet mass balances, then momentum balances, heat balances and component mass balances. Happel's[4] concept of money balances is a useful extension of this training. One characteristic of any such balance is that the balance is made over some region or envelope and it is on the commodity money. The overall craracteristics of chemical industry are discussed first. A detailed look at specific processing systems is obtained by functional and structural analyses. Equipment design and safety considerations are discussed. This material is often supplemented by a visit to a local firm that has this process. Next, methods of cost estimation and of reporting the financial attractiveness of proposals are presented.

Developing the General Principles of Devising Economic Balances and of Optimization. Now that the students appreciate the two necessary ingredients for economic balances, they learn to combine them into balance equations. The general strategy for developing the equations is presented, and the application of the strategy is outlined. The problem of handling uncertainties (as described by Rudd and Watson[5]) can be introduced but because of time limitations that material usually has to be reserved to the graduate course. Nevertheless, the uncertainty because of limited calculational time is a topic the seniors should master. This includes making good assumptions, minimizing calculational time and project planning. A variety of optimization techniques are briefly outlined. Depth was gained only with Golden section and dynamic programming. This section of the course draws heavily from Rudd and Watson.

Applying the Principles to Industrial Problems of Expansion and Efficiency. The principles are then applied to many cases to illustrate the fine points. First, problems are given to illustrate the application of the strategy to design. These cases are carefully selected for their open-endedness and their ability to illustrate different aspects of the strategy. Secondly, problems illustrate plant improvement through changing operating conditions, replacement studies and through troubleshooting problems.

INNOVATIONS ATTEMPTED

Course descriptions convey only part of the concept about any course. It is the emphasis and new ideas tried that probably provoke the most interest. The students had difficulty in defining open-ended problems, and they had trouble setting up economic balance equations. They could see how one might approach an optimization problem but did not see how the expression for the objective function was obtained. They had difficulty being creative—or generating alternatives, and they could not see what types of assumptions were needed if the calculation time was limited. The students could easily memorize the design morphology but did not put the information to work when they tackled realistic problems, had difficulty in asking the right questions when such an opportunity was afforded them, and did not appreciate that all aspects of chemical engineering including plant operation could be challenging and exciting. Innovations were introduced to attempt to overcome these problems. Here is what was tried and the results.

The students did not appreciate that all aspects of chemical engineering including plant operation could be challenging and exciting.

Functional Analysis of Processes and In-plant Lectures. Although students had some industrial experience they did not appreciate what goes together to constitute a process. In addition they should be introduced to a spectrum of practical know-how and safety: such simple things as steam traps, barometric legs and pressure relief valves. Practice in defining problems should be introduced early in the program. In addition they should gain confidence in their ability to generate alternatives. All these can be satisfied by doing a functional analysis of a process. Often the process selected is that used in the project laboratory.[1] The functional analysis technique is adopted from value engineering.[10] The analysis steps are:

1. Classify the major sections of a process,
2. define the functions of each piece of equipment,
3. rephrase the functions to eliminate semantic barriers,
4. generate alternatives that satisfy the functions using free-wheelings brainstorming sessions, and
5. evaluate the alternatives based on technical feasibility.

To promote discussion it is useful to require each student to bring to class a flow diagram of a process to serve a given function. That is, the students are given the raw material in a given condition (e.g., soya beans in bags sitting on the deck of a ship docked in Burlington Bay) and a required end product (e.g., deodorized soya bean oil in a large storage tank, lecithin in drums and bagged soya pulp stored in a warehouse). The major steps of reaction, purification and or separation, and changing the physical form are identified. Then from the collection of flow diagrams a typical flow diagram is selected. For the typical diagram each piece of equipment is identified by number to avoid later semantic difficulties. The next step is to critically define the primary and secondary functions of each piece of equipment. This is done by the class as a group. If there are more than three primary functions, then we attempt to reevaluate the functions. Next the function statements are rephrased in words that are the least restrictive and yet appropriately describe the function. For example, one function might be to "dump the soya beans from the bags." This is rephrased to "separate the soya beans from the containers." The substitution of "containers" for "bags" allows us to think of the possibility of using other types of containers for which the separation step might be cheaper. Then, the class period is devoted to brainstorming. No criticism is allowed; all ideas are accepted. When the generation of ideas starts to slow down, the introduction of outlandish or far-out possibilities usually starts a deluge of new ideas. To preserve the brainstorming atmosphere, it is useful to consider about four pieces of equipment at a time so that the brainstorming session can last a full class period. The use of overhead transparencies aids in keeping track of ideas from session to session.

A sample worksheet illustrating a student's attempt to do a functional analysis on his own is given in Figure 1.

The ideas suggested during the creative brainstorming sessions are then criticized. This is an excellent opportunity to describe technology and know-how that they have not experienced before. Sometimes we take one of the 'wildest' ideas and see how we would attempt to make it work. Here, it is emphasized that unless an idea is presented

FIGURE 1. SAMPLE FUNCTIONAL ANALYSIS WORKSHEET

Functional Analysis of **Soya Bean Plant**

ITEM	FUNCTION	GENERATE ALTERNATIVES
Soya Beans in Bags	Separate Soya Beans from container	Cut open and dump { machine / manually Grind up bag & beans and separate via density, cut top open Dissolve the bag Burn away the bag Roast away the bag
Miller Hopper	Direct beans to transportation system: meter flow; buffer hold-up; protect from weather	Tank with conical bottom. Pile on floor in covered building & dozer; Store as bags on the floor & carry.
Conveyor	Transfer beans from storage to cleaning units; meter flow	Conveyor belt; bucket elevator; gravity; continuous pneumatic conveyor; discontinuous, high pressure conveying system; carry them; float them; blow them; lift them, float conveyor with air/with water/short them, blast them.

The students see that the separation of the creative from the critical mental stages brings about practical ideas that would probably be lost if attempted together.

or created it cannot be analyzed. The students also see that the separation of the creative from the critical mental stages brings out practical ideas that would probably be lost if the creative and critical stages were attempted together. That is, we tend to dismiss as 'unworkable' valuable creative ideas if we criticize as we create.

This classroom exercise can be greatly enhanced if it can be complemented with a visit to a local company that has a similar process.

At McMaster, the process often selected resembles the operation of the local industry Canadian Vegetable Oil Processing Ltd., that handles soya beans. The student now can see some of the equipment discussed during the functional analysis and understands some of the reasons why it might have been selected. We discuss what the student might do if he was working for the company and if a given piece of equipment was to be replaced. Later a frank discussion with company personnel about present operating problems helps to illustrate the value of functional analysis as sound background work for any process.

From an instructor's viewpoint, this approach is easy to do and well worth the time. The approach is enhanced immensely by the in-plant visit, and the process chosen for the class functional analysis was determined by the availability of such an opportunity. The in-plant visit was unique in that it was **not** a plant tour. **We were** permitted to go about the plant on our own; we were not given a plant tour by company personnel. We spent as much time as we wanted discussing among ourselves any aspect of the operation.

This functional analysis technique introduces plant know-how, illustrates the importance of clearly defining problems and lays the foundation for all creative activity for the rest of the course.

Another in-plant lecture is arranged later in the course to illustrate trouble shooting problems and to again introduce practical design techniques. This lecture concentrates on a three-tower distillation unit and was arranged through the cooperation of Mr. E. W. Blackmore, Domtar Chemicals Ltd.

The in-plant visit was unique in that it was not a plant tour. We were permitted to go about the plant on our own.

Devising Economic Balance Equations. Students have difficulty in doing cost balances over pieces of equipment because they do not recognize an overall strategy for tackling large, open-ended, cost-oriented problems and because of their inexperience in defining problems. They also have difficulty establishing a uniform accuracy level demanded for the problem. This affects their choice of fundamental and cost details that they include in the balance.

To combat this the emphasis on the course is essentially on how to apply a consistent, organized strategy and how to define problems. The background information given to the students describing a consistent strategy is outlined in reference 11. This is supplemented by several detailed examples to illustrate the application of the strategy. Happel's[4] examples; p 182ff, and in Appendix B; are easy to recast into the strategy; they are simple enough that the students do not become overwhelmed by details. This material is the backbone of the course and a lot of time is spent devising balances and defining problems.

Balancing Calculational Time with Accuracy. Knowing what assumptions to make so that an open-ended problem could be solved in the available time is a challenge that most students had difficulty in overcoming. The available time for calculations can be divided into three sections:

1. time to define the problem, make assumptions and select the equations needed, t_e minutes.
2. time to collect the input constants, physical properties, and cost operating and equipment data, t_p minutes
3. time to actually perform the calculations, t_c minutes

That strategy suggested is shown in Figure 2. In general information on this problem was difficult to locate.

To appreciate how an engineer might select assumptions the medium chosen was the imaginary conversation between a knowledgeable but novice engineer, E, and a devil's advocate, DA, suggested by Rudd and Watson. The students found this conversation approach very interesting; so interesting that it was worthwhile to recast previous course illustrative material into this format. A unique way to present this material was to let the students role-play and attempt to develop the conversation themselves. The mechanics were:

1. to prepare the conversation ahead of time,
2. divide the class into two to play the two roles
3. the students playing each role would try to state or answer questions according to their respective role without the aid of the conversation sheets; that is, those playing the role of the DA would try to formulate the best question to ask. While they were doing this, those playing the role of the E could look at the prepared conversation sheet to see the suggested question. Through interplay between the students playing the E roles and the instructor with the students playing the DA roles the DA's eventually pose a question similar to the prepared question on the conversation sheets. Then, the play is reversed, the E's must answer the posed question. The DA's and the instructor can see the answer on the conversation sheet and through other questions the DA's care to pose the E's answer the question.

Sample conversations are given by Rudd and Watson.[7]

The students had already had experience with locating information through a sophomore course on "Information Management and Technical Writing."[12] Hence, they did not have much difficulty in realistically estimating time t_p.

The students did not have much experience in estimating the required calculational time for large systems involving a lot of recycle. Class material, examples and problems were based on the material of Rudd and Watson.

In general, the overall concepts were difficult to get across and much development work is needed for this part of the course.

FIGURE 2. SUGGESTED STRATEGY FOR BALANCING TIME WITH ACCURACY

DEFINE and PLAN	1	Determine things needed for the calculation of the answer. List all and study contribution of each to the accuracy of calculated answer. (Is the contribution significant?)
	2	List the alternative equations that can be used to calculate each contribution. Try to list in the order of decreasing calculation time.
CARRY OUT and LOOK BACK	3	Estimate the three times, t_e, t_p, and t_c, and compare these with the total time available for each combination of equations and constants.
	4	Select the combination of equations and constants that can be used in the time available and that will yield consistent accuracy in all the contributions.

Computer-aided Optimization. The objective of this part of the course was to introduce some ideas, concepts and methods available for optimization. Methods of optimizing the use of optimization techniques were deferred to the graduate course. Some depth was given in only two areas.

Emphasis was placed on selecting criteria. Although financial attractiveness is the commonly accepted criteria, the importance of technical, time and resource, environmental, originality in design, social, product acceptance and market-volume feasibilities were discussed. The use of a decision matrix of all these criteria was discussed following the guidelines suggested by Dean **et al.**[3]

The depth was gained—without having to resort to a time consuming computer programming exercise—through the use of mathematical models developed in a simulation project from previous years.[1, 2, 6] For example, an optimization program for a single decision variable search using Golden Section and for the single bed reactor to convert sulfur dioxide to sulfur trioxide had been developed by Professor C. M. Crowe. Since four beds with intercoolers are used on the plant the class used dynamic programming to optimize the conversion to sulfur trioxide with bed inlet temperature as the decision variable. The students enjoyed the exercise and felt it well worth the time.

Trouble-shooting Problems. The third section of the course on the application of the principles to design and process operation depends mainly on the judicious selection of problems that can most effectively illustrate problem diversity as well as the uniformity of strategy used. This section most aptly is described as a series of case studies. An innovation tried was to use trouble-shooting problems for plants that have already been designed. Their use emphasizes the diverse applicability of the strategy and shows that plant operation presents challenging problems. This technique[7,8,10,11] and some sample problems are described elsewhere. The instructor has a variety of ways in which these problems can be used: individuals solving the problems,[13,11,14] group solution to the problem, and group defining a strategy.[8] This past year we experimented with the group solution to the problem. In this approach the group discuss the strategy, decide on an action and pose this action through the instructor (who acts a Devils Advocate and screen for the questions) to a teaching assistant who supplies realistic answers to the proposed action. This approach allows the group to experience more problems in a given period of time. However, the individual does not suffer the consequences of his own action. Now, through the cooperation of Shell Canada Ltd, we are developing short film loops to present the problem to the students with visual impact!

SUMMARY

A four-credit senior course presents a background understanding of 'what is a process,' cost estimation techniques, introduces a strategy that can be used to define problems and to devise economic balances, and surveys methods of choosing criteria and choosing the best. Many problems or short case studies are used to apply these concepts to real industrial problems of both design and process operation.

From past experience the major difficulties encountered by the students were in defining problems, devising economic balance equations, being creative, making good assumptions, applying design morphology, and asking the right question. To overcome these and other difficulties, several innovations have been tried.

Functional analysis of plants or parts of plants together with in-plant lectures have been useful and interesting to the student. Here the primary and secondary functions of pieces of equipment are defined, alternative means of satisfying the functions are generated through creative brainstorming sessions and the resulting alternatives are later critically analyzed through group discussion for technical feasibility. In-plant lectures then were used to illustrate a system, and opened the discussion of feasible design and operating conditions.

A second innovation was the emphasis placed on devising economic balance equations. Similarities in strategy for tackling large, open ended aspects of handling uncertainty were discussed following the guidelines of Rudd and Watson.

Teaching the students how to make good assumptions so that the problem can be solved in the allotted time was not very successful. Perhaps this is too harsh a judgment because evaluation is difficult. The media used was a strategy plus examples and a 'role-playing' session illustrating the conversation between a novice engineer and the devil's advocate.

Optimization techniques were briefly surveyed; selection of criteria was emphasized and some details of one optimization technique were given. The detailed look at a dynamic programming solution for a two stage system with a single decision variable for each stage was possible because of the availability of the computer programs.

Trouble-shooting problems were used as short case studies where the students played the role of an engineer trying to get a plant functioning correctly for a minimum cost. This innovation was enthusiastically received by the students.

ACKNOWLEDGMENTS

I am grateful to Mr. S. G. Boulter of Canadian Vegetable Oil Processing Ltd, and to, Mr. E. W. Blackmore, Domtar Chemicals, both of Hamilton for allowing me to use their facilities for the in-plant lectures, and to Professor Dale F. Rudd and C. C. Watson who have introduced me to some exciting concepts and approaches in this field. My students and colleagues at McMaster have offered suggestions and support to some of the experiments tried.

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CHEMISTRY FOR CHEMICAL ENGINEERS*

P. H. WATKINS
Esso Research and Engineering Company
Linden, New Jersey

Dr. Watkins is employment coordinator for the Esso Research and Engineering Company. He holds BS, MS, and PhD degrees in chemical engineering from Virginia Polytechnic Institute. Dr. Watkins taught at VPI and in 1956 joined Esso at Baton Rouge in development engineering. He was a campus recruiter and may visit your campus—watch for him.

The type and amount of chemistry required in the Chemical Engineering curriculum has been a controversial topic over the years. Chemistry is an important part of the undergraduate curriculum and the practicing chemical engineer continues to need a thorough understanding of the fundamentals of inorganic, organic and physical chemistry and the theory and techniques of analytical chemistry. Since he will use chemistry as one of his tools in his decision making processes, the courses should emphasize application and problem solving. His chemical engineering courses in turn should offer him the opportunity to apply his chemical knowledge to the maximum amount possible.

It is a pleasure to discuss with you the very critical question of what chemistry should be included in the chemical engineering curriculum. I think the fact that we are willing to discuss this

*Presented at the Annual Meeting of ASEE, June 19,-22, 1967.

. . . Unwanted or deleterious side reactions . . . will rise up and smite him in both catalytic and recycle processes.

topic is an indication of the dynamic nature of our profession. I also think it is an area that must be approached with some caution. It is true that many chemical engineers are now making noteworthy contributions in areas where no knowledge of chemistry is required. On the other hand, I feel very strongly that a professional cannot be termed a *chemical* engineer unless he has a solid and usable understanding of the major fields of chemistry. Conversely, to be a chemical *engineer* also implies a thorough background in the principles of engineering. These two requirements pretty well define what the technical content of his education must be, and the trick is obviously one of finding an optimum balance between the two.

Before discussing the problem of how much and what kind of chemistry, it might be well to remind ourself of what general procedures will be expected of the chemical engineer on any project he may be involved in. I think in almost any case he would be expected to demonstrate the abilities to:

1. Find and identify the problem or problems in the project.
2. Plan a successful approach to solve these problems using such analytical and synthetic approaches as are required. Problem will usually be open ended.
3. Prepare a sufficient number of solutions (cases) to define alternatives available.
4. Make a decision based on the facts as developed.
5. Report this decision in a clear, concise manner.
6. Be sufficiently versatile to modify this decision on his own initiative when environmental factors change.

While these requirements will not say what kind of chemistry our chemical engineer should study, it does imply how it should be taught. He will obviously be using his chemistry as one of his tools in his decision making. Therefore, all his chemistry courses should emphasize problem solving, and his chemical engineering courses should challenge his chemical knowledge to the maximum. After all, the chemistry department is only responsible for giving him the tools. The chemical engineering department bears the responsibility of showing him how to use them. Accomplishing this objective will require cooperation and much discussion between the departments involved as well as separate and collective discussions between these departments and the users of the product of their labor. Fortunately, as this meeting exemplifies, these informative exchanges are becoming more and more a part of the overall educational process. In passing I think one should give the "Goals" committee and the "Preliminary Report" a lot of credit for stimulating these discussions.

Turning now to the chemistry content of the Chemical Engineering curriculum, I think we would all agree that undergraduate and graduate education will have to be looked at separately. The bachelors degree must prepare a man for beginning positions in industry and government as well as for graduate school. In the former groups he would most probably start in one of the following areas: development, design, operational analysis, technical service, operational supervision and technical sales. To prepare him for this multiplicity of opportunities it seems to me that he must be well grounded in inorganic chemistry, organic chemistry and physical chemistry. He will also require a foundation in the techniques of analytical chemistry. I think it goes without saying that he should obtain these courses as early as possible so that he may start using them.

Inorganic chemistry will, I imagine, continue to be the basis of a freshman course. I would hope that the emphasis here would be on good old-fashioned equation balancing and lots of good experience in handling stoichiometric type problems. Some of the concepts of physical chemistry should also be introduced at this time, but only those concepts which he has the mathematical background to grasp and to apply to problem solutions. While I agree that there may be a real need on campus for a broad, descriptive type of introductory course in chemistry designed to give a student an overall appreciation of the field, such a course should not be considered for the young engineer.

In the field of analytical chemistry one can generate arguments for complete exclusion or very heavy inclusion into the curriculum. My view is a moderate one and I believe the chemical engineer should have sufficient exposure, both theory and laboratory, in the techniques so that he will have a feel for the reliability of these data in his problem solving. I would also like to see considerable emphasis placed on instrumental methods, since these techniques are and will be useful in his in-line control problems.

would you like to write "The Formation of Perhydrophenalenes and Polyalkyladamantanes by Isomerization of Tricyclic Perhydroaromatics?"

How's that again? Well, never mind —Bob Warren, Ed Janoski, and Abe Schneider already wrote it. They're chemists in Sun Oil Company's Research and Development Department. Their paper is just one of many resulting from imaginative and original basic research conducted at Sun Oil.

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In organic chemistry there should be a good balance between synthetic and mechanistic work. I think it would be good to place emphasis on some of the problems that will plague him later, such as unwanted or deleterious side reactions. As we all know these will rise up and smite him in both catalytic process and recycle processes. It would also be a good thing for him to obtain an understanding of the effect of structure on physical as well as chemical properties. Many of these men will spend large portions of their careers in product rather than process work.

In physical chemistry I think we would agree that we are looking at the basic science he will use most. Coverage of thermodynamic, kinetic, and equilibrium considerations should be intensive. The only plea I would make is that it be kept general in nature and that we fight the temptations to make it a specialized course in atomic physics, or any of the other attractive fields that have only marginal professional utilization for the average engineer.

In summary, the fields of chemistry and their manner of presentation discussed above seem to me to represent the minimum requirement, and represent somewhere around 30 semester hours of instruction. Additional courses such as biochemistry, colloid chemistry and so on may be highly desirable on an individual elective basis, but do not seem to be general requirements.

The problem of chemistry at the graduate level is obviously much more on a case to case basis. The man who plans a career in process or product research work should certainly broaden his chemical knowledge. On the other hand, the man who aims toward the area of applied mathematics in the separational and diffusional areas may have little need for additional courses unless his local chemistry department is very active in these particular areas. In practice he will probably obtain his additional training in his own department. The terminal masters man going for design has little need for additional chemistry. The same is true for the man aiming for management rather than a technical career. I do not believe that it is really possible to suggest any overall definitive additional chemistry training beyond the undergraduate education. In the final analysis we are engineers, not chemists, and while our problems are involved with process and product, they are engineering problems. Our problems frequently include chemical considerations, but very rarely to the exclusion of all others. In our graduate training it seems to me that we should provide the chemical training necessary to perform the chemical engineering research or development area the student is specializing in. We should not confuse this with the chemical training requirements of the research chemist.

I would like to see considerable emphasis placed on instrumental methods since these are useful in in-line control problems.

In summary, chemistry has been and is an integral part of the training of the chemical engineer. He needs to be well grounded in the fundamentals of the principal branches of chemistry. Of equal importance he must be trained in the application of these fundamentals to his problem solving and decision making activities. As he specializes in graduate work, he should be exposed to those branches of chemistry which contribute to his specialization. Finally, we must constantly remember that chemistry is only one of the many tools of his profession, and that his exposure to this science should be in relation to need and not precedent.

ChE news

Dr. Paul Murrill, professor and head of LSU's chemical engineering department, was one of two college professors in the nation to be presented the Faculty Service Certificate by the National University Extension Association's Division of Conferences and Institutes. Dr. Murrill was recognized for a series of short courses which he developed in the area of computers and their uses. A member of the LSU faculty since 1963, Dr. Murrill has also been awarded the $1,500 Halliburton Award for excellence in engineering teaching.

Dr. Richard H. Wilhelm, chairman of the chemical engineering department at Princeton University died August 6. He was the featured educator in the Spring 1968 issue of CEE. Recently he was appointed to the National Academy of Engineering and he presently held the prestigious Henry Putnam University Professorship at Princeton.

ChE educator

FRANK GROVES

FAVORITE PROFESSOR

An outstanding teacher who participates actively in research, consulting, and in both local and national AIChE activities is featured in this issue as our "ChE Educator"

Ten years of inspiring teaching in chemical engineering has won Dr. Frank R. Groves, Jr., of Louisiana State University the reputation of "master teacher." But in addition to his classroom ability, he has been cited as a scholar and a researcher.

The 39-year-old Louisiana native has been teaching a wide range of subjects including most of the University's undergraduate course offerings in chemical engineering. Among these are material and energy balances, thermodynamics, fluid flow, transport processes, heat, mass and momentum, properties of gases and liquids, and mathematical models. At the graduate level he has taught thermodynamics, distillation, reactor design and scale-up theory.

LSU's chemical engineering students in 1966 named him "Favorite Professor." In the following year he was awarded one of four Halliburton Awards for excellence in teaching in the College of Engineering. The awards emphasize the importance of quality instruction and encourage the development of excellence in the organization and presentation of engineering course work. The Halliburton program at LSU is designed to reward individual professors who have made contributions beyond that expected in the normal performance of their duties.

Dr. Groves served on the faculty committee which directed revision of the LSU chemical engineering department's curriculum several years ago, and he has also helped prepare new course materials for the department. He has been a guest lecturer in the American Society for Engineering Education's visiting engineer program and has written 11 research papers for publication or symposium presentation. His teaching has extended to off-campus courses for industrial personnel throughout Louisiana.

Like his teaching interests Dr. Groves' research interests have been broad. A unifying thread of interest in problems related to chemical reactor design holds together his diverse individual projects. These have included digital computer studies and experimental work on variable temperature absorbers, a project in the pure chemistry of an oxidation reaction catalyzed by a complex ion, various digital computer studies on variable temperature reactors, computer analysis of supersonic combustion for ramjet engines, and an investigation of vapor-liquid equilibria in non-aqueous solutions. Most of these studies have been described at technical meetings and several have been published in the permanent technical literature.

Dr. Groves has supervised many MS theses and four PhD dissertations during his service at LSU. Three of his PhD students are employed in industry—one in aerospace, another in petrochemicals, and the third in organic chemicals. The latest will begin a career in university teaching this fall. His MS students are scattered over the United States in various industries.

Aside from his work at LSU Dr. Groves has been active professionally in a number of other ways. He has spent two summers at Oak Ridge National Laboratory working on the fluoride

ChE Division Chairman for 1968-69: W. H. Corcoran

The new chairman of the Chemical Engineering Division of the American Society of Engineering Education is Professor William H. Corcoran, Executive Officer, Department of Chemical Engineering, California Institute of Technology, Pasadena, California. Professor Corcoran has recently served as Executive Board Member and as Chairman of the Publications Board for the Division and it is largely through his leadership and personal efforts that **Chemical Engineering Education** has received excellent financial support from industrial corporations and universities.

Professor Corcoran has been a member of the Cal Tech faculty since 1952 as Associate Professor and then Professor of Chemical Engineering. Prior to that he had been Director of Technical Development for Cutter Laboratories. He has been active in the AIChE having served on the National Program Committee as Chairman of Group 7, Education and Humanities and as a member of Group 4, Fundamentals. He is also serving on the Student Chapter Committee and the Membership Committee.

Professor Corcoran is active in various civic and religious groups. He is the author of numerous papers and several books dealing with kinetics, thermodynamics, transport phenomena, and other areas.

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- John O'Connell, University of Florida
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Publications Committee Chairman—James H. Weber, University of Nebraska.

Program Chairman—Kenneth Bischoff, University of Maryland.

Continued from page 172.

volatility process for treatment of spent nuclear fuel elements. Another two summers were spent at NASA's Langley Research Center working on computer analysis of supersonic combustion in ramjet engines. He is a member of the American Chemical Society and has been active in the American Institute of Chemical Engineers serving as vice-chairman, chairman, and member of the executive committee of the Baton Rouge Section. He served as a member of the Technical Program Committee for the 1967 Houston National Meeting of AIChE and has been active in consulting work with Columbian Carbon Company since 1962 first at Lake Charles, La. and now at Princeton, N. J. where he has consulted on various aspects of organic process development.

Dr. Groves is currently working under a NASA contract on improvement of a computer program describing supersonic combustion. This project is a small part of a NASA research program aimed at developing ramjet aircraft for flight in the hypersonic range (5 to 12 times the speed of sound). Next year he will be directing a project at LSU on drying of porous solids for Cabot Corporation.

Dr. Groves was born in 1929 in New Orleans, Louisiana, and received his elementary education in the public schools of that city. He entered Tulane University in the summer of 1945 and received a BS in Chemical Engineering in 1950 and an MS in Chemistry in 1951. He attributes his success in teaching a wide range of courses to the broad basic training in science and engineering provided at Tulane.

While studying chemistry at Tulane he was fortunate to have as major professor Dr. Hans B. Jonassen, who aroused an interest in research on complex ions, which has persisted up to the present time. With the encouragement of Dr. Jonassen he entered the University of Wisconsin in 1951 and continued his fundamental studies in chemical engineering receiving the PhD in 1955. Following graduate school, Dr. Groves spent four years in industry including two years with Atlantic Refining Company and one year with Texas Instruments Inc. in Dallas, Texas. He married the former Margaret Hodge of Dallas in 1959. They have one son, Frank D. Groves, 8 years old.

ChE department

CALTECH

WILLIAM H. CORCORAN
Executive Officer

BRIEF HISTORY

Chemical Engineering at the California Institute of Technology began with the appointment of William N. Lacey as Instructor of Chemistry in 1916. He had been a student of Professor Gilbert N. Lewis at the University of California at Berkeley, obtaining his Ph.D. there is 1915. Dr. Arthur Amos Noyes, previously acting President of M.I.T., and then Professor of Chemistry at the California Institute of Technology, proselyted Will Lacey and initiated a long and fruitful association. The general style in Chemical Engineering at Caltech is based upon thinking that stems from the attitudes of G. N. Lewis, Arthur Amos Noyes, and W. N. Lacey.

In 1927, API Project 37 was initiated for study of volumetric and phase behavior of hydrocarbons and is just terminating after 41 years of a very active and contributory life. Will Lacey was the founder of this effort and was joined by Bruce H. Sage in 1929. The collaboration between the two has had a major effect upon the production and processing of petroleum and hydrocarbon compounds throughout the world.

As World War II approached, the California Institute of Technology became deeply involved in work on naval ordnance and subsequently on army ordnance. Professors Sage and Lacey led the Chemical Engineering group in work on interior ballistics of naval rockets and on processing of double-base propellant for the manufacture of solid-propellant grains for those rockets. In addition to research and development efforts in this area, a significant semi-works plant for the production of naval rockets was operated by the Chemical Engineering group in the San Gabriel mountains. These efforts were part of the program at Caltech in an integrated effort on the total development and supply of naval rocket ordnance. Toward the end of World War II a significant amount of the group's effort was directed toward ordnance work associated with the Manhattan Project. In the main, however, the contribution in naval rocketry was the principal endeavor.

After World War II, Chemical Engineering began development of a PhD program and a broadening of its research interests. That program has continued on successfully. Because the California Institute of Technology is a small school, opportunities for close association among the students and the faculty members in both the classroom and laboratory are great and are fully utilized.

AIMS AND GOALS

From 1916 onward, the aim of Chemical Engineering at Caltech in its educational program has been to focus upon fundamentals of physics, chemistry, and mathematics with overlying concepts of chemical-engineering design as a foundation for the development of professional skills. That attitude still prevails today, and all the planning is made with that thought in mind.

Because of the stress on fundamentals, chemical engineering at Caltech has never gone heavily into the development of a unit-operations laboratory. Laboratory work in chemical engineering, both for BS and MS programs, has been mainly directed toward the study of fundamental phenomena with emphasis on the integration of point-by-point information on temperature, pressure, and composition to understand the total perform-

Our goal is not to produce specialists . . . who would gravitate to a given area of activity in the scientific and engineering world. Our graduates are occupied in activities ranging from investment banking to medicine . . .

ance of a piece of equipment. At the time of graduation from Caltech, the BS or MS student in chemical engineering has not had the sophistication that some other students may have had relative to operation of process equipment. Because of the finite time available for education, it is believed that the limited time in laboratory work is better directed to the study of basic principles and that application of these principles to real problems is best treated in the classroom by way of case studies of varying degrees of length and difficulty.

Inasmuch as the school is small, there has been unlimited opportunity to try various techniques in the teaching of chemical engineering at the undergraduate level as well as at the graduate level. Of major concern at the moment is how to maintain association with principle and still provide some degree of sophistication for the student relative to the explosion of technological information. The approach has been to remove courses and to add new, upgraded courses still based on fundamentals but providing new case studies with origins in the newest technologies. The incoming freshman student improves from year to year so that the procedure of removing courses and bringing in new courses with continual upgrading has not been too difficult to follow.

The elimination of courses is one of the great challenges to all curricula. One of the pitfalls in the planning of educational programs is the tendency to add new courses without removing old ones. That has not been one of the problems at Caltech. An examination of today's undergraduate curriculum shows that it is different from the curriculum of three years ago, quite different from that of six years ago, and so forth.

With the goal of providing an education as well as a degree of competency in dealing with chemical-engineering principles, it has been necessary to focus more and more upon a course in the senior year of the undergraduate program which would integrate the thinking of the student relative to various courses he has had as an undergraduate. That integration currently is done in the framework of a course entitled "Optimal Design of Chemical Systems." In this course there is application of studies in applied mechanics, strength of materials, properties of materials, unit operations, and optimization to the design of real chemical processes, both of the type encountered in the chemical-process industry and of the type that might be encountered in less traditional areas such as in biological, medical, and aerospace fields. The approach has resulted in a decrease in the traditional number of hours devoted to applied mechanics and electrical engineering, but perhaps an increase in sensitivity to the concepts of engineering if one might define engineering as the application of fundamental principles of science to economic and social needs. Throughout all our teaching, we emphasize that the knowledge which is being discussed is eventually to be applied to provide a profit in an industry or to provide some assistance to the Federal Government and its manifold problems or to help society in its problems of economics and progress.

Our goal is not to produce specialists at the BS level or MS level or even the PhD level who would all gravitate to a given area of activity in the scientific and engineering world. We would be unhappy, indeed, if all our graduates went into the aerospace industry alone or into the petroleum industries alone. Our graduates are occupied in activities ranging from investment banking to medicine with certainly great emphasis in between on the chemical-process industry which represents a major part of our country's strength.

Size of student body is important to us but not in terms of providing us with larger and larger numbers of students. We seek a number of students we believe is an equitable proportion of the total enrollment. Caltech's total undergraduate student body currently numbers about 700 and the graduate student body about 800. Our goal is to achieve 15 undergraduate chemical engineers per class for the current level of the total enrollment of undergraduates. In the past decade the undergraduate program at Caltech has been most attractive to physicists and mathematicians. A change is occurring, and in the 1968-69 year for the first time there will be an elective course in the freshman year that will allow the student to associate with some part of engineering. Therefore he will have an early opportunity to learn something about engineering which has not been readily possible in the past. That change in curriculum along with the belief that there is a renaissance among technical students to consider the economic and social needs of society suggests that the goal set by us for our undergraduate enrollment in chemical engineering could be realized in a relatively short time.

We currently have 42 students working for the PhD degree. Of those students, 36 are majors in chemical engineering, and 6 have majors in other options. Over the next 5 to 6 years we seek to increase that enrollment to about 55 graduate students. Currently we have 9 faculty members, and that level will change to about 11 members over the next five years. So, as a rule of thumb, we hope to maintain about five graduate students per academic staff member. Our goals are clear, and we believe we understand how to meet them, but with all projects this day, the unique and fine combination of men, money, and time is not a simple task. We intend to maintain our operation on the relatively modest basis described and believe that it is very compatible with Caltech's goals.

OUR STAFF

The interests of the 9 members of the Chemical Engineering staff at the California Institute of Technology are varied. A broad attack of various problems in the areas of chemical engineering and applied chemistry exists.

Professor Bruce H. Sage has been involved in the research activities since 1929. His laboratory for studies of both equilibrium and non-equilibrium behavior in hydrocarbon systems continues to make major contributions to knowledge in those areas. Out of that laboratory has come some 300 scientific papers, and 8 books co-authored by Professor Sage. The petroleum industry has been significantly aided by the efforts of Sage, Lacey, and co-workers over the past four decades.

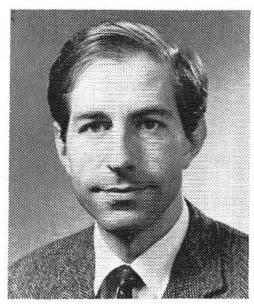
One of the world's outstanding laboratories for study of liquid-state physics and chemistry has been established by Professor Cornelius J. Pings. Both experimental and theoretical studies are employed in the development of a more unified means of predicting physical properties of liquid systems. Professor Pings' presentation at the meeting of the Faraday Society in April of 1967 on the determination and analysis of radial-distribution functions in liquid argon using X-ray diffraction is of special note and was excellently received by liquid-state experts. In addition to the real progress being made by Professor Pings in the attack of the liquid state, he has continued to make interesting and significant contributions to optimization studies as they relate to situations near chemical equilibrium.

Pings

Friedlander

Professor S. K. Friedlander is on joint appointment between Environmental Health Engineering and Chemical Engineering. His current major areas of research are air pollution and biomedical engineering. Studies of aerosols in the atmosphere are of special interest in his efforts. Significant work is being done in the biomedical field. He and one of his students just completed a fundamental study of gas-exchange with flowing blood, and the information will have application in the design of extra-corporeal systems for medical use, especially in heart-lung equipment. In further work associated with the lungs, Professor Friedlander and colleagues have proposed a new and more accurate method for the calculation of particle transfer rates by diffusion at bifurcations in the upper respiratory tract.

Tschoegl



Gavalas

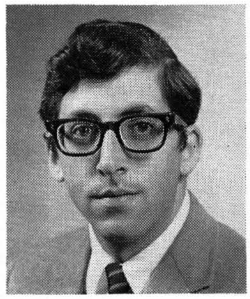
In 1967 Professor N. W. Tschoegl joined the staff of the Chemical Engineering Laboratory. The major activities in his group are directed toward the study of the molecular basis of the mechanical behavior and fracture of filled and unfilled elastomers. Problems of deformation, yield, and fracture are continually found in general engineering applications of polymers as well as in the very important area of solid propellants for rocket motors. Cooperative studies of crack propagation in filled, viscoelastic materials are being conducted with Professor W. G. Knauss of the Aeronautics Laboratory.

Professor G. R. Gavalas, who studied at the University of Minnesota with Rutherford Aris, is involved in the application of modern mathematical techniques to a variety of chemical engineering systems. His primary interest is in systems in which there are chemical reactions in the presence of heat and mass transport. His significant contributions in this area have culminated in the preparation of a monograph which is to be published soon. It is entitled "Non-linear Differential Equations of Chemically Reacting Systems."

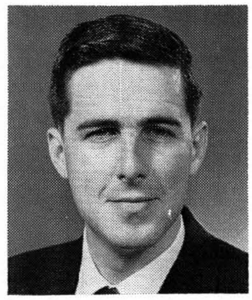
Plasma chemistry and physics are of major import in many laboratories today, and Professor Frederick H. Shair is deeply involved in studies of transport and chemical change associated with plasmas. Recently he developed a theory of cataphoretic transport in binary mixtures subjected to DC glow discharges, and it is in agreement with essentially all available data. Currently he is investigating cataphoretic separation in flow systems with emphasis upon the development of an economically attractive method for purifying helium to better than 1 ppm. In his kinetics studies, he is presently conducting experiments aimed at relating electron densities, collision frequencies, and energy distributions to the overall yields and reaction rates associated with reacting gases in glow discharges and in coronas. In all of his studies, he is concerned with energy balances and scale-up. He and Professor Gavalas are collaborating in the study of certain aspects of plasma kinetics.

Additional activity in the area of biomedical studies exists in the laboratory of Professor Giles R. Cokelet. He began the study of the rheology of suspensions in his work at M.I.T. with Professor E. W. Merrill and has continued his activity at Caltech. Of particular interest to him is the rheology of blood and the nature of blood flow in small-bore tubes. Professor Cokelet will be leaving Caltech in January of 1969 for appointment as Associate Professor at Montana State University, but it is hoped that his general area of interest will receive continuing consideration at Caltech. That emphasis is natural in its complementary and supplementary relationships with the work of Professor Friedlander within the department.

A recent addition to the Chemical Engineering staff is Professor John H. Seinfeld who did his PhD studies with Leon Lapidus at Princeton. Without any loss of momentum, he has continued his interests at Caltech in the areas of optimization and adaptive control of chemical systems. Currently he is studying the problems of optimal control of stochastic systems and the control of systems with time delay.



Vaughan



Seinfeld

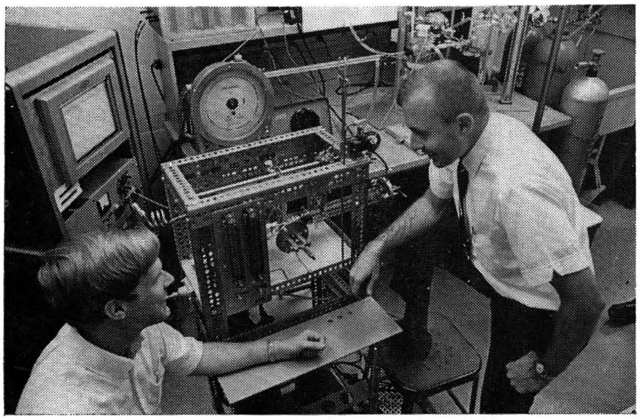
In the first half of 1969, Chemical Engineering will be happy to receive as one of its new colleagues Dr. Robert W. Vaughan, who currently is a lieutenant in the Army on duty at the Jet Propulsion Laboratory of the California Institute of Technology. Dr. Vaughan completed his work at the University of Illinois under Professor Drickamer and has been specifically interested in the study of the electronic structure of metals, particularly iron, at pressures up to 3 million pounds per square inch. Mössbauer spectroscopy has been his main attack to the problem, and he plans to continue his work in Mössbauer spectroscopy as part of his program at the California Institute of Technology.

My interests continue in the area of applied chemical kinetics with emphasis on reactions of nitric oxide. In addition to work at room temperature, work is proceeding on studies of reactions of nitric oxide at temperatures between 3000 and 6000 °K in an argon plasma. Separate from the studies on homogeneous reactions, work is under way with Professor Thad Vreeland, Jr., of Materials Science on a continuation of previous interests in the role of dislocations as they affect surface reactions catalyzed by single crystals of silver.

THE FUTURE

Hopefully without chauvinistic overtones, my belief is that chemical engineering is the most viable engineering discipline in the world today.

That viability stems from the consideration that chemical engineering must combine chemical and physical phenomena in the application of knowledge to real problems of society. As has been repeated probably too many times already, we cannot alone concern ourselves with physical change but must be deeply concerned and involved in



Prof. Shair (right) and student.

knowledge and application of chemical change. This involvement and concern is the operating base for the future of chemical engineering at Caltech. Each of the research areas described above has as its ultimate focus the opportunity to improve our ability to cope with problems involving chemical change. This concept is what we try to communicate to our students. For that reason we will continue to have ever-increasing and strong reliance upon physical chemistry as the basis of our efforts. We do that not without diminishing our preoccupation with problems of economics and engineering analysis. The economics and engineering analysis should still be directed, nevertheless, toward the control of chemical reactions.

How are we best to achieve that goal at Caltech? That question is answered by considering the great opportunity for any chemical engineering department, and especially our department at Caltech, to involve itself in interdisciplinary efforts. No other engineering discipline is better situated to have the opportunity to move in various directions in association with departments on a given university campus. We at Caltech are extremely fortunate in this opportunity inasmuch as any real or imagined blocks to communication are essentially zero. We have no problems whatsoever in reaching out and working in cooperation with Electrical Engineering, Materials Science, Biology, Chemistry, Physics, Geology, and other groups on campus. If we do not take the fullest opportunity to work with these groups and to enhance our education and research as well as theirs, we are failing in our goal. We are already developing stronger ties in the area of research and have embarked upon improved interdisciplinary efforts in the teaching of our laboratory work in chemical engineering. In the past year, in fact, there has been extraordinarily good success and cooperation between Professor Shair and Professors E. E. Zukoski and R. H. Sabersky of Mechanical Engineering in the teaching of a senior and first-year graduate course in engineering laboratory. Professor Shair has led the way in the development of experiments involving chemical change, and Professors Zukoski and Sabersky have brought in improved ideas reative to dealing with problems in energy and momentum transfer. That type of thinking must continue in various other avenues and in the coming year will be expanded in the already mentioned cooperation between Electrical Engineering and Professors Seinfeld and Gavalas in the teaching of a course in control. Again, the principles that are being taught and studied will not change significantly, but the technological background for the students will be improved greatly by bringing in new ideas on how to cope with older principles. An electrical-engineering student can gain by having the opportunity to hear from chemical-engineering professors regarding the jargon and problems associated with the control of various chemical processes. In turn, the chemical-engineering students will gain significantly by having the opportunity to have electrical-engineering professors communicate their points of view on control.

Our next major goal in the effort to improve our total attack here at Caltech in chemical-engineering education is to examine how we deal with applied physical chemistry throughout the campus. My hope is that Chemical Engineering will be a part of making significant change and progress in the improved teaching of applied physical chemistry by the various disciplines that incorporate this field of study in their curricula.

The future is exciting here at Caltech, and the responsibility for us as chemical engineers is great. We must be especially alert because we have special problems in being sure that we understand the full meaning of dealing with both chemical and physical change in the face of the opportunity for significant interdisciplinary contributions.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ChE book reviews

As I Remember, Stephen P. Timoshenko; tr. by Robert Addis.
D. Van Nostrand Company, Inc. Princeton (1968) pp. xi + 430, 14 ill. $9.75.

Professor Stephen Prok'yevich Timoshenko, whose widely-used textbooks and other scholarly works are familiar to every engineer, wrote his memoirs in Russian and published them in Paris in 1963 when he was eighty-five years old. These memoirs were translated into English in 1967.

The Bolshevik Revolution forced many Russian scholars to emigrate. Timoshenko was one of the most outstanding of these. He came to the United States in 1922 when he was forty-four years old and through his work in industry and as a professor, first at the University of Michigan and later at Stanford University, became known as "the father of engineering mechanics" in the United States. His memoirs should be of interest not only to engineers and scholars but to many other people as well. He had a successful career as an engineering teacher in Czarist Russia. He was a contemporary of the fictional Dr. Zhivago and people who have read the late Boris Pasternak's book or who saw the excellent film based on it will be interested in Timoshenko's comments on his life in imperial Russia. American engineers may be surprised to learn from this book that engineering education in Russia before World War I was far superior to engineering education in the United States at that time. However, thanks to efforts of many men like Timoshenko this is no longer true.

One of the reasons that these memoirs make such entertaining reading is that they are so fast-moving. The author traveled widely, met many interesting people and was a keen observer of the engineering scene. The story of Timoshenko's escape from the chaos that was Russia during the revolution is particularly absorbing. He did not return to his homeland until 1958 when he went there to inspect engineering schools. He reported the results of this trip in a 1959 book and in a memorable article in the November 1958 *Journal of Engineering Education.*

This remarkable book by a remarkable author is recommended to all readers of *CEE*.

DAVID H. KENNY,
Michigan Technological University
Houghton, Michigan

ChE views and opinions

STUDENTS, FACULTY AND PROFESSIONALISM

RICHARD GRISKEY, *Former Chairman*
Department of Chemical Engineering
University of Denver

The most important resource of the University is the student. The only task of the University is to nurture—to make the student grow to be a creative and productive member of society. These are rather simple contentions, and there may be people who disagree with me about their importance. It is my feeling that, today as never before, students are being very badly neglected at most of the Universities in this country. This is true in any field of endeavor: engineering, liberal arts, or business. I can cite many instances to show that this neglect actually exists.

If we walk on a campus today we see some characters who look as if they were turned loose from some southern California cult. They have hair running down their backs, beards and togas, and all kinds of weird customs. We see students who are protesting everything including protest, and others who are wearing buttons that say "acid." These types are everywhere across the country. We see students who are walking around saying: "Who am I?" "What am I?" "What am I doing?" "Where am I going?" We see people "dropping out" or "turning on." We see in our own society a very great lack of professionalism. We wonder what causes this and why it takes place.

I agree wholeheartedly with John McKetta that professional development is certainly a life long proposition. But I think if we examine the facts, we will find that the very first contact that a student has with the professional man (some of you might question calling professors professional men) comes at the University. And as the old saying goes 'As the twig is bent, so grows the tree."

But what is or could be wrong with the attitude in most of our universities? I cannot generalize as any generalization is incorrect, including this one. However, if we look at the attitudes of our faculty, I think that they do not, in the main, lead to the kind of attitudes that are needed for professional growth.

What is wrong with these attitudes? I will cite actual cases. One professor in one institute has a little egg timer—it goes for three minutes. A student comes in, "Professor Jones, I have a question." He turns the egg timer on, "You have three minutes." By the time the student stumbles and stutters through about a minute and a half, he never gets into the question. "Your time is up, leave my office, I am a busy man." Professor B. keeps his door locked. He is a very busy man. He has no time for students. He has to generate his committee work, his papers, his research, all his activities. To spend time advising students is just a little bit beyond him; he just can not take the effort to do it. Professor C. writes letters of recommendation for his students, and he does a wonderful job of damning them with faint praise. A typical example of Professor C.'s letter is the one he is supposed to have written for Jesus Christ. It went something like this: "This man is rumored to have founded a great religion; however, there is no evidence to show that he was other than mediocre in his chosen profession of a carpenter." These are not isolated examples. I find instances of such lack of contact with the faculty all the time when talking to students whether they are transfers, graduates, or actual employees in industry. They say, "The faculty does not really care what hap-

Dr. Griskey received his BS, MS, and PhD degrees from Carnegie Tech. He has served in the U. S. Army, in chemical industry, and in various levels of academe including department chairman. At present he is Director of Research and Foundation Research Professor at Newark College of Engineering.

The purpose is to make students grow . . . not to beat them down

pens to me," or "nobody wants to take the time to advise me."

Somebody may say, "Well, yes, this is fine for you as Denver is a small private school, but what about the larger state universities?" I maintain that even at large schools there must be advising, there must be contacting, and there must be guidance. The contrast between schools is indicated by what some interviewers told me. For instance one of them said, "It's remarkable a couple of your students have actually improved in college the last two years. You don't seem to have the attitude they have at some schools." I said, "What do you mean?" He said, "Well, at some schools they seem to be trying to drive all of them out of engineering—to fail them all out." I think this unfortunately, is the attitude of many professors. We are all busy, and everybody has things to do: you must write papers; the Dean is on your back to get a couple of research contracts; somebody else wants you for this or that. I think this means that University professors, instead of working the sixty hour week that Dean McKetta talked about, must work almost a one hundred twenty hour week. It means that if a professor has nothing more to do in his office all day than to advise students, he ought to be doing it.

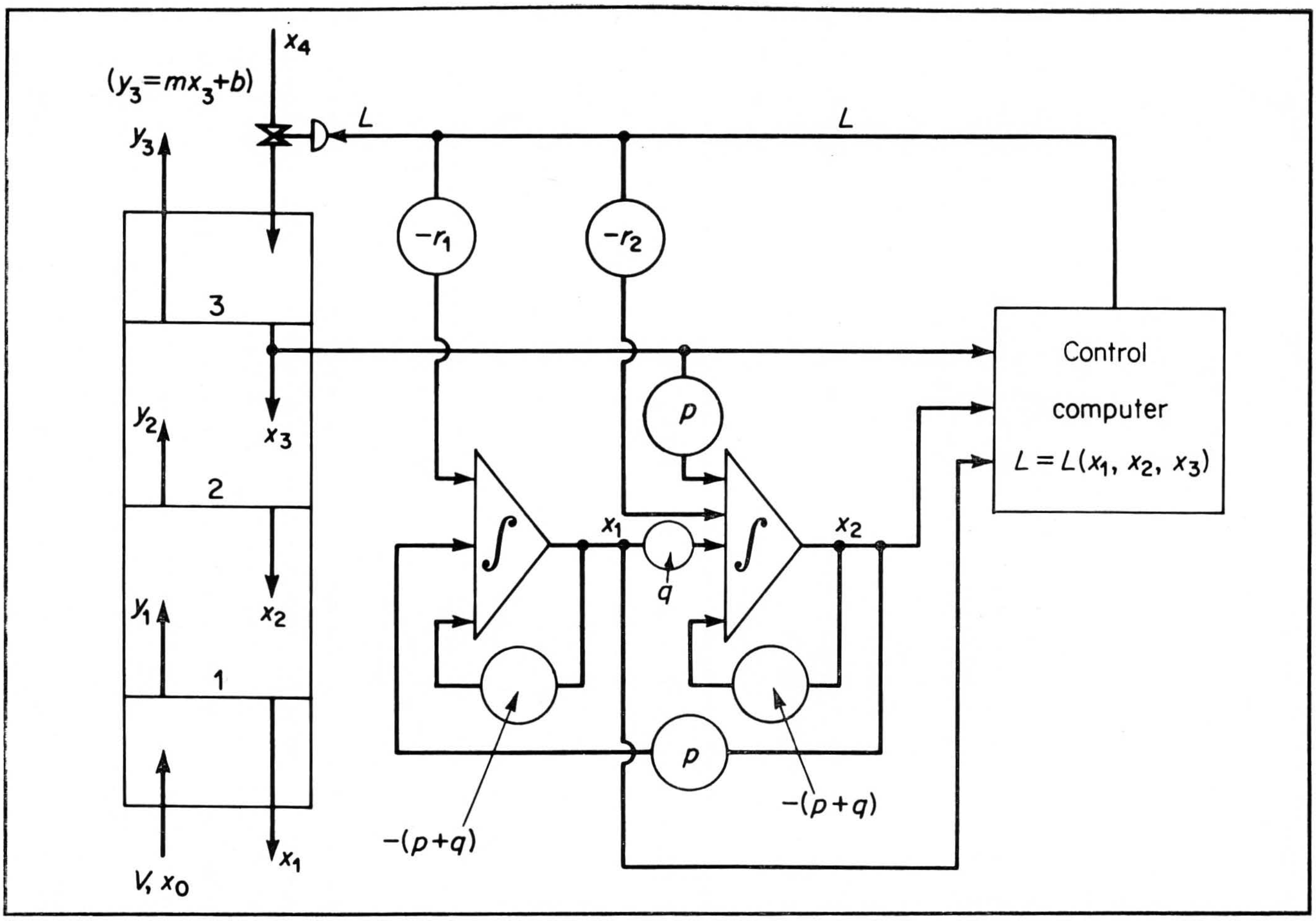
I find that even our younger professors in engineering, the so called "bright lights" or "high flyers," on the research side have an anti-student attitude. I recall one of them at another campus, as students were trouping in for registration, saying to me with a disgusted look on his face, "Wouldn't it be wonderful if they just weren't on the campus?" My own attitude is if they were not on the campus there would be no reason for the campus' existence. I think that all of the professors must feel toward the students much as one might feel toward a younger brother or sister, or, depending upon age, toward a son or daughter.

The purpose is to make them grow. It is not to beat them down—it is not to demolish them. It is to instill into them the attitude called in the army "esprit de corps," which is pretty much undefinable, but I think most of you can sense the difference. In baseball they call it hustle, maybe in engineering we call it "professionalism." The lack of professionalism, evident in many graduates, comes, I think, from a lack of concern on the part of the faculty.

Who is at fault? Is it the faculty only? Well, I do not personally think it is the faculty alone. To indict the faculty is to say that it is not doing the job while everybody else at the University may be. I think the whole concept of the University really must change in some ways. Schools have become very impersonal places. The administration runs the college or university as a business proposition. Because it is a business proposition, the earlier concepts of teaching and living and working with the student have gone out the window.

Of course, it requires an interested faculty. The faculty must want to work with the student, to build up his "esprit de corps," to increase his professionalism. Help must come from higher levels also. It should come from department heads, it should come from deans, and it should come from provosts. These people must do more than pay lip service. If they have faculty members who are openly antagonistic to the students, then such members ought to be called in and told: "Well, look, I don't care if you have 90,000 papers. I don't care if you are on all these national committees. If you don't have time for students then you're not part of this University. You'll have to go elsewhere." I do not think that there is enough, if any guidance by the people that are in the prominent places in the education profession. However, one does not get any dollars for such activities and maybe this is wrong. Concern for students never shows when the time comes for pay raises, or publication counts, or comments like, "Well, I hit the Department of Defense for $200,000 last year in the game of grantsmanship." I think work with students is the most important activity one can do. If a professor can develop one student—just one—it is worthwhile. If he can take one boy or girl that is failing, set him or her on the right course, and help him or her become a useful and productive member of society, then the professor has done something beneficial.

I am not going to say that every college and every university has staff members that do not care. But I do think that the "Berkeley syndrome" is unfortunately too often the case at many of our schools. I remember a remark one young faculty member made to me: "You know one of the problems is that too many of the professors think they are too good for the students." And I think this is true. I think until the attitudes change, until you feel that "by golly I want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to get in there and work with these students," not much can be done. I do not mean mollycoddling of students. Some people may say, "He's advocating leading them around by the hand." No, I do not mean this. When a boy comes in and says: "I've got six job offerings. How about telling me about these companies?"—or he says: "Gee, I'm thinking about going on to grad school, but I really don't know."—or he says: "My freshman math instructor has failed 95% of the class." —I believe the professor ought to be doing something. I think that he ought to be asking questions. He ought to act as the inspector general, if nothing else.

In other words, the professor ought to be concerned and interested in the student, and he ought not to be concerned as much in pleasing various administrators. Doing what is right for the students is much more important than fulfilling a set of paper regulations. Let me also say that I have written quite a few papers. I have time to participate in national meetings, and I get quite a bit done. But, I have never shut my door to a student. I do not think anybody on my staff at Denver has either. I think this should be the tenor at all schools. If this forces one to work in the evening or on week ends, then one must. But advising a student who might be standing out in the hall with his knees shaking—a freshman or sophomore—is much more important than writing any paper or doing anything else. I maintain that if you inspire the student with the right attitudes he will continue to grow when he goes into industry. He will take off in the right direction, and he will be primed to walk the second mile that Dr. McKetta talked about.

ACKNOWLEDGMENTS

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ChE problems for teachers

We continue with the thermodynamic problems and solutions prepared by Professors Irey and J. H. Pohl at the University of Florida.

1. An incomplete equation of state for a substance with the work modes $-EdZ$ (associated with charge) and PdV (compressibility) is written as;

$$\frac{V-V_0}{V_0} = \beta\, T + K\, Z\, P$$

a. Determine the electric potential, E, as $E = E(V,T,Z)$.

b. Calculate the difference in internal energy

$$u\,(T,V,Z) - u\,(T,V_0,0)$$

due to changes in volume and charge.

c. If $C_{V,Z}(T)\Big|_{\substack{V = V_0 \\ Z = 0}} = C_{V_0,0}(T)$

find $C_{V,Z}(T) - C_{V_0,0}(T)$.

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