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Prediction of Temperature and Oxygen
Distributions In Aerobic Microbial Growth
S. FINGER, T. REGAN, T. CADMAN AND R. HATCH

Tubular Flow of Pseudoplastic Fluids
C. WEINBERGER

Analog Simulation of Sample-Data Systems
M. RUTKOWSKI AND P. DESHPANDE

Identity, Breadth and Depth in a Co-Op Program
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ALSO: Too Much ChE Research and Teaching
Is Dull ... Dull ... Dull, H. McGEE

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**CALL FOR PAPERS FOR TRANSACTIONS
IN ENGINEERING EDUCATION**

Sir:

The American Society for Engineering Education expects to begin publishing an annual *Transactions in Engineering Education*, beginning in December, 1975. Its purpose is to provide a medium for the publication of high quality articles that are of significance and long-lasting interest to the engineering education community. The articles may pertain to any aspect of engineering education: educational research, learning theory, teaching methods, review of on-going projects, administration, organization, guidance, finance, technical research as it pertains to education, and other areas.

The articles may be of any length appropriate to the subject, but on the average are expected to be about 2,400 words. All articles will be carefully reviewed by referees expert in engineering, engineering education, and appropriate allied disciplines. Criteria for selection will be based on the significance of the subject to engineering education, quality of the treatment, and long-lasting value of the article.

Papers to be submitted for the first annual issue should be sent, in five copies, by May 15, 1975 to me at the following address: Bureau of Engineering Teaching, ECJ 10.322, University of Texas, Austin, Texas 70712

Dr. Billy V. Koen

MODELING, SIMULATION AND OPTIMIZATION

Sir:

This is an announcement of our summer program on "New Developments in Modeling, Simulation and Optimization of Chemical Processes" to be held at Massachusetts Institute of Technology on July 28 through August 6, 1975. This special summer program will present basic principles and techniques for computer-aided design and control of industrial-scale chemical processes. Topics to be covered include steady-state process simulation, process optimization, dynamic modeling and simulation of chemical process synthesis, and comprehensive problem-oriented computing systems for chemical process design. For further information, please contact: Director of the Summer Session, M.I.T., Room E19-356, Cambridge, Mass. 02139.

Lawrence B. Evans

**FUNDAMENTALS AND APPLICATIONS
OF MINICOMPUTERS**

Sir:

For the third consecutive summer, a short course entitled, "Fundamentals and Applications of Minicomputers" will be offered by the Center for Industrial and Institutional Development at the University of New Hampshire. This course is designed for the engineering/manager who must have sufficient awareness of the applications of minicomputers to enable him to specify and utilize them in his operation. Participants with and without computer experience will benefit from this integrated

treatment of minicomputer concepts. For further information write: CIID, Kingsbury Hall, U. of New Hampshire, Durham, New Hampshire.

Audrey Savage

APPLIED NUMERICAL METHODS

Sir:

The University of Michigan announces an engineering short course this summer in "Applied Numerical Methods to the solution of practical engineering problems and their implementation on digital computers. The course will be held June 23-27, 1975. For additional information write U. of Michigan, Ann Arbor, Michigan.

Viola E. Miller

PRINCETON'S 1975 SUMMER COURSES

Sir:

Here is a roster of our 1975 Summer Courses in Continuing Engineering Education. **June 9-13:** Perturbation Techniques and Differential Equations, W. Sirignano; Three-dimensional Descriptive Geometry and Computer Graphics, Y. Hazony, S. Slaby; Digital Signal Processing, K. Steiglitz. **June 16-20:** The Statistical Design of Engineering Experimenta, J. Hunter; The Design and Analysis of Railroad Tracks, A. Kerr; Modern Process Control, R. Andres, E. Johnson; Advanced Modeling of Combustion in Internal Combustion Engines, F. Bracco; Groundwater Hydrology and Pollution, R. Cleary. **June 23-27:** Water Pollution Science and Technology, R. Cleary; Prediction for Production and the Arts of Charts, J. Hunter. **July 7-11:** The Numerical Solution of Ordinary Differential Equations of Engineering Importance, L. Lapidus. **July 14-18:** Mathematical Methods of Engineering Analysis I, A. Cakmak. **July 21-25:** Mathematical Methods of Engineering Analysis II, A. Cakmak. **August 4-8:** Compiler Design, J. Ullman, T. Szymanski; The Finite Element Method in the Simulation of Contaminant Transport Processes in Hydrologic Systems, G. Pinder, W. Gray. **August 18-22:** The Finite Element Method in Surface and Subsurface Hydrology, G. Pinder, W. Gray.

If there are any questions write: Summer Course 1975, Princeton University 08540.

Joyce W. Dean

**CACHE
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CHEMICAL ENGINEERING EDUCATION, in cooperation with the CACHE (Computer Aides to Chemical Engineering Education) committee, is initiating the publication of proven computer-based homework problems as a regular feature of this journal. Instructions for submission of problems appears on page 38 of the Winter 1975 CEE or can be obtained by writing Dr. Gary Powers, Carnegie-Mellon University, Pittsburgh, Penn. 15213.



CHE DIVISION ACTIVITIES

Program at the 1975 Annual Meeting

Submitted by Prof. William D. Baasel of Ohio University

Would you like to know how your department should be financed, how your curriculum should be changed, how to properly train foreign students, how to obtain research grants, or how to act as an expert witness? Then come to the ASEE annual meeting at Colorado State University from June 16 to June 19, 1975. A program on each of these topics will be presented by your division, the Chemical Engineering Division of ASEE. Besides this, there will be hundreds of other events plus women's and children's programs. We hope to see all of you there.

There are five sessions which the chemical engineering division of ASEE will be sponsoring and another which it will be cosponsoring. One of these events was thought to be of such importance, that it has been designated a miniplenary. It concerns the method of financing a university and departments within a university. It is entitled, "Should a University Be Run Like a Business".

Many universities, both public and private, are having financial problems today, and it appears that they are likely to increase rather than diminish. In 1978 the number of people reaching the age of 18 will peak. From then on for the next decade, at least it is predicted the number of students entering our American universities will decrease. There are some predictions that there will be ten to fifteen percent fewer students in higher education 10 years from now than at present. With fewer students this will mean less tuition money, and hence a greater financial pinch.

Whenever there is a financial crisis there are attempts to reorganize, and currently that trend is taking the form of running the university system within a state as a large business. Many universities receive subsidies based on the number of students they attract and retain. It is recognized that engineering, medicine, dentistry, and agriculture, cost more to operate, and these programs receive higher per capita support than the liberal arts programs. However, within a given area, the support of the program is based on the student credit hours generated. This leads to problems. In the early 1970's when the engineering enrollment

dropped one third, many schools had to fire faculty and curtail course offerings. Now as the enrollment is on the upswing, the reverse occurs and other areas of the university are feeling a cost squeeze.

Harold Enarson, the President of Ohio State University, in an editorial in the Sept. 7, 1973 issue of *Science* noted,

To the new managers, the university is just another large system. It has raw material (students), a labor force (faculty and support personnel), instruments of production (classrooms, laboratories, libraries), a production schedule (academic requirements, classes admitted, and classes graduated), management (the trustees and central administration) and a production index (the cost of producing a student credit-hour). The managerial revolution creates the exact reverse of the goals that are sought. The impact of multiple sources of regulation on the university is to discourage flexibility, cripple initiative, dilute responsibility and ultimately to destroy true accountability.

Universities have always had the problem of evaluating teaching and research. For the latter, one could count publications. Teaching, however, has defied any such quantitative evaluation. Now there is another such dilemma. The quality of one program compared to another defies qualitative measurement, while the cost of producing a student credit hour can easily be determined. A three hour monolog per week by a professor may not be as beneficial as a self-paced course or an open laboratory, but it may cost less. Lecturing to 500 students in freshman psychology is more profitable than a senior elective course in modern control theory and practice. Yet the control course may require more effort by the instructor. A chemical engineering department may have no course which is required by other majors with which it can pad its student credit hours. The equipment in some laboratories may be too expensive to duplicate, so the number of students per laboratory is kept low and the cost high.

The very important problem of relating the quality of education to its cost will be addressed by five panel members at the 1975 annual meeting

(Continued on page 79.)

TOO MUCH CHEMICAL ENGINEERING RESEARCH AND TEACHING IS DULL . . . DULL . . . DULL

H. A. McGEE, JR.
*Virginia Polytechnic Institute
and State University
Blacksburg, Virginia 24061*

WE ARE LIVING IN ONE of the most exciting, challenging, and potential-laden times in the history of the profession of chemical engineering. In response to these crucial times, one would imagine that the academic departments of chemical engineering at the universities of our land would be uproarious centers of ferment and activity. All too frequently they are not such centers however, for when judged by what could be done, much of what actually does occur in campus laboratories and classrooms can only be described as dull . . . dull . . . dull. Astonishing.

THE PROFESSIONAL CALLING

BEFORE THINKING ABOUT chemical engineering in particular, let us look at university professors as a class. Certainly a central element in the behavior of professors is academic tenure—that phenomenon so incredulous to our industrial colleagues whereby a professor of chemical engineering, or of any other discipline, *must* be, not *may* be, granted absolute job security for life. The tenured professor cannot be removed, and certainly a developing professional atrophy or incompetence are not viable grounds for even questioning his status. Or, as my colleagues would say, rather he then becomes a department head.

Our universities are also very special enclaves that are in their own way extraordinarily provincial. This apartness from the world is dramatically evident in the distinctly Leftist position of most professors on political and social questions. Leftist speakers who openly advocate even murder and the violent overthrow of the government receive the rapt attention of university

audiences, while mildly Rightist types are hooted off of the lecture platform. In contrast to this far liberal perspective on other peoples' problems, professors are typically extreme conservatives—far to the right of Barry Goldwater—in their views of their department, or their discipline, or their own personal affairs. The concept of tenure is sacrosanct and no consideration of its possible modification can be tolerated. Meaningful curriculum revision is extraordinarily difficult, and affirmative action is the only proper moral and social perspective, until, of course, *my* department is expected to add or is prohibited from releasing a patently unqualified woman or black.

A third deterministic element in the profession of professorship is the commitment to research and creative scholarship. There are, of course, the scholarly and pedagogical arguments of the importance of basic research, of the importance of basic research, of the necessity of a current faculty, and of insuring a vigorous and intellectually stimulating environment. But



Henry A. McGee, Jr. is a scientist/engineer by education and by experience. He is professor and head of the ChE department at VPI & SU. His current research interest is the application of very unusual high energy chemistry to the development of highpowered chemically pumped lasers. He is active in AIChE and this essay is abstracted from a popular invited talk he has given around the country as an AIChE Tour Lecturer. His comments on teaching and research are as a participant rather than as an observer. The critique, "which is as much self-directed as otherwise, is meant to be good natured, but with a sharp significance."

academic prestige and economic factors have also played a non-trivial role. Anyone who, like the physicists, can make a bang as enormous as that of a thermonuclear explosion or who can otherwise change the character of our national life, just must be reckoned with, and this enchantment has continued through the development of nuclear power, the space program, the environmental and ecology movement, and now the energy problem. The broad economic implications of new high technology industry that springs from good research are also very compelling, and these are perhaps most visible around Cambridge and Palo Alto. Thus all universities now insist upon research as well as teaching. To gain professional esteem, a professor must be an able grantsman; and thereby the evaluation of the worth of a professor is performed only in part by his on-campus peers and superiors. Rather it is the granting agencies in Washington who significantly determine the fate of the aspiring professor.

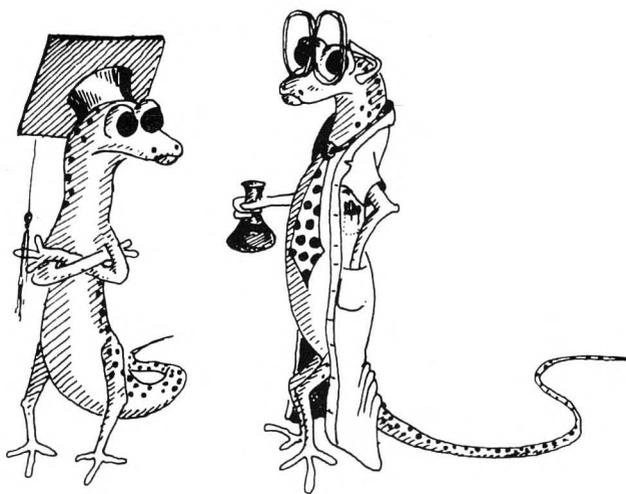
Enormous expansions in enrollments have meant similar expansions in the numbers of adults employed to instruct these young people. Hence there are both many more professors than ever before, more of them spend more time on "research" than ever before, and the scientific literature is, not unexpectedly, growing as never before. Not just in chemistry at Harvard and Wisconsin, or in theoretical physics at Caltech, or in biochemistry at Berkeley, but all institutions subscribe to this doctrine that is now somewhat tritely referred to as "publish or perish."

EGALITARIAN COMMITMENT

AS CONFIRMED ADHERENTS to the conventional liberal wisdom, professors as a class are also very egalitarian and very intense about things like civil liberties and democratic due process. Therefore the wisest decision on any question is that resulting from discussion—seemingly interminable discussion—and voting. This equality idea also means that the most innovative and creative people are frequently neither sought for faculty appointments nor do such people necessarily find the idea of an academic career to be inherently attractive. Few professors of music, for example, would be happy with the idea of a Burt Bacharach or a Leonard Bernstein as a professional colleague. And as in all democratic organizations, the purposes and goals of the university or the department must then be defined in such a way that all can contribute. Respectable

research must be defined in a way that the average professor of rather ordinary abilities can extend the scholarly frontiers and fill the scientific literature. In addition, and in complete harmony with our egalitarian commitment, we divorce excellence in a skill from learning about a skill, for otherwise the gifted individual would be at an advantage. Our universities then often employ teachers of engineering without especial regard to whether they themselves are also good engineers.

Let's look at a few of the techniques used by professors, certainly not overtly with devious in-



Why should we worry if nobody cares about our results. Yeah—it's scholarly, it's correct, it's publishable, and besides we're tenured!

tent, but rather naturally and involuntarily, to form and to shape the bounds of what we at the universities know as respectable scholarship.¹

For example, please realize that a professor can devote his entire career to teaching and scholarship, publishing many papers in learned journals, giving talks at meetings of his professional society, being well recognized by his peers, without ever once running the slightest risk of being wrong about anything that he has ever published or said. Not infinite wisdom, but rather this requires only that one carefully structure the kind of knowledge that he seeks. How can one be wrong about p-V-T measurements? Or vapor-liquid equilibria? Or pressure drop measurements? The worst that could happen would be technical problems of perhaps a poorly calibrated thermometer. Thus rather than inventive thinking, most professors tend to gather data, and usually even that is in areas where the results will be unexceptional, where broader interest

is meager, and where one cannot possibly be in error on other than some minor technical point.

Industry contributes in its own way to this state of affairs, for clearly a company will only support work at a university that is non-sensitive, or that which will in no way compromise patent positions, or that which is tedious and uninteresting to the in-house research force. In short, industry supports only that academic work that is technically located where the real action is not. There are good reasons for this, but they are reasons that we must carefully reconsider, because change toward a more mutually beneficial sym-

Once only the brightest minds delved into mathematical abstractions . . . but the democratic idealism of most professors prohibits any thought that perhaps theories are best left to superior minds. With patience, a Taylor Series expansion, and the aid of the computer anyone can and does author a theory today.

biosis of industry and academe is essential. This necessity for change has and will continue to promote many thoughtful discussions, but let us here not digress from our exploration, not of the needed changes, but rather of the effect at the universities of the now prevailing attitudes.

PROPER SCHOLARSHIP

PROFESSORS ARE STRONG PROPONENTS of experimental procedures and equipment. Our scholarly publications tend to be recitations of the technical or logical consequences of the application of this or that method. Multi-valued problems in which decisions hinge upon creative insight or hypotheses or perhaps on just plain hunches are shunned. Thus all knowledge becomes forced to be like geometry or thermodynamics wherein the answer to the problem may be logically deducted from the problem statement. The great complexity and variety of scientific equipment is of particular value in this pursuit of "proper scholarship." We have System 370's, mass spectrometers, nmr machines, esr machines, ESCA machines, and the like that are sufficiently large, expensive, and complex to readily convince both one's self and one's peers of the high scientific merit of his work, when in reality the work is frequently more commonplace than it is imagina-

tive. The jargon and the technical complexity can then satisfactorily mask the unexceptional and even trivial merit of the activity.

Although it is only a part of the human personality, professors insist upon submerging all else in a single-minded pursuit of total objectivity, passion and emotion are shunned, and it is essential that one be diligently neutral regarding the outcome of his scholarship. Academe has almost lost the contrasting attitude that although objectivity is essential, when it is all alone, it surely represents a severe truncation of real knowledge in the real world applied to real problems.

The egalitarian commitment of academia has also radically altered the concept of a theory. Once only the brightest minds delved into mathematical abstractions of the nature of reality. Einstein, Schroedinger, and more recently the Bardeen, Cooper, Schrieffer theory of superconductivity and the rules on the reactivity of organic compounds first proposed by Woodward and Hoffman are examples of these rare and grand insights. But the democratic idealism of most professors prohibits any thought that perhaps theories are best left to superior minds. With patience, a Taylor Series expansion, a sort of crude pleasure in number crunching, and the aid of the computer anyone can and does author a theory today. And the scientific literature is full of wonderfully complex notations, and constructions, and perhaps sometimes even mathematically elegant descriptions of the commonplace.

To interpret these observations as anti-truth or counter to the scientific method to which we all pledge allegiance is to miss the point entirely. Rather we wish to show how professors can easily and inconspicuously and unknowingly mask their lack of real scientific and engineering creativity by their concentration on the analytical as opposed to the synthetic aspects of any question. Thus the nature or the shape or the kind of knowledge that is being produced by faculty members is a strong function of the personality traits of the professors themselves. This circumstance is self-perpetuating, for the exceptional student, who is by definition, the student that is analytically astute though perhaps not aggressive or innovative, receives maximum reinforcement and naturally emulates his mentors. Just as naturally, he gravitates into an academic career of his own—and the situation continues.

(Continued on page 94.)

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ChE department

NEWARK COLLEGE OF ENGINEERING

DEPARTMENT FACULTY

*New Jersey Institute of Technology
Newark College of Engineering
Newark, New Jersey 07102*

CHEMICAL ENGINEERING AND CHEMISTRY have been major educational elements since Newark College of Engineering initiated degree programs in 1919.

Recent changes have brought about a new institutional name, New Jersey Institute of Technology, (under which Newark College of Engineering continues as a cohesive form for engineering education); a new multi-million dollar facility; and a continuity of curriculum updating. A seasoned faculty with long experience at the Institute has had exceptionally positive relations with NJIT undergraduate and graduate students, as

well as a record of active participation in all important aspects of the institution and of professional life.

In recent years the department graduated an average of 100 chemical engineering students per year—roughly 80 B.S., 18 M.S. and two D.Sc. students per year, a far cry from its first graduating class of three, more than a half century ago.

A particularly distinctive aspect of the educational operation is the affiliation and relationship of the members of the two allied divisions of the department—chemical engineering and chemistry. Cooperative ventures in interdisciplinary research, multidisciplinary graduate and undergraduate curricula, and collaboration on departmental curricula changes are routine practices. From a table of organization viewpoint Chemistry has 17 faculty members and Chemical

Engineering 13; but from a viewpoint of academic realities the two divisions act as one in considerations affecting the department.

As a stable and senior department of the Institute, Chemical Engineering/Chemistry employs an excellent reputation on campus for its approach to teaching, research educational activities, student relations and involvement in active faculty governance.

Within the professional societies there has been a long record of active participation in AIChE, ACS and ASEE, represented by many different forms of local and national organizational involvement.

DEPARTMENT HISTORY

NEW JERSEY INSTITUTE OF TECHNOLOGY (NJIT) started as Newark Technical School in 1881 and has operated under a number of names in its 90-year history. Originally funded by community leaders and later by a joint commitment by City and State, the Institute still enjoys an arrangement by which the State contracts with the Board of Trustees for the providing of education. The original purpose of the Institute 90 years ago was to provide a wealth of skilled talent for New Jersey industry; in large respect this purpose still stands since the majority of chemical engineering graduates, as well as those of other engineering disciplines, are absorbed into the tremendous variety of regional industry.

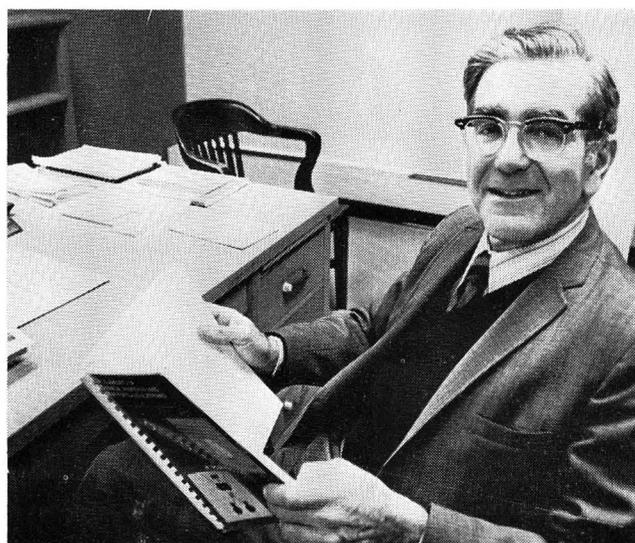
When formal degree programs were organized in the Fall of 1919 chemical engineering became one of the first degree-granting departments, capitalizing on the strength of existing chemistry courses and related offerings. While titled Chemical Engineering, instruction in chemistry continued, establishing the rapport that continues in certain aspects today.

Another interesting feature of NJIT's department is the strength-in-service of the faculty and

In recent years the department graduated an average of 100 ChE students per year, roughly 80 B.S., 18 M.S. and 2 D.Sc. students per year—a far cry from its first graduating class of three, more than half a century ago.

particularly the fact that only a few men have headed the department in more than 50 years: the late Vernon T. Stewart served as chairman from 1920 to 1946. An institutional reorganization in 1946 separated chemistry and chemical engineering administratively for 20 years. Under this arrangement Dr. M. Lelyn Branin headed chemistry and Dr. Charles L. Mantell was brought in from industry to readjust chemical engineering offerings to post-war professional needs.

Curriculum was revised, courses in plant design and chemical engineering kinetics were introduced; a master's program in chemical engineering was started in 1947 and AIChE accreditation for the undergraduate curriculum was received in 1950. Student interest in professional societies revived and the AIChE chapter was reinstated.



Joe Joffe, Chairman of Chemical Engineering and Chemistry.

In 1963 Dr. Mantell retired and Dr. Joseph Joffe was appointed chairman of chemical engineering; Professor George C. Keeffe, who had long been associate chairman, continued in that role. In 1966, upon the retirement of Dr. Branin as head of chemistry, the two areas were reunited as one department under Dr. Joffe. The continuity of department fidelity is perhaps best noted by the fact that Dr. Joffe will retire in 1975 with 43 years of service and Professor Keeffe in 1976 with 40 years of service.

Among the many factors that have contributed to the growth and productivity of Chemical Engineering/Chemistry at NJIT was the gift of a nearby industrial building in the 1950s which enabled the department to provide the facilities necessary for large undergraduate and graduate operations.

While some new buildings were added in the post-war years, NJIT's city location precluded any extensive expansion until the 1960s when urban renewal and several State college bond issues encouraged wholesale growth. NJIT's campus was able to expand from five buildings on two acres to more than a dozen on 20 acres, the most notable and latest of which is the new \$7 million chemical engineering/chemistry complex.

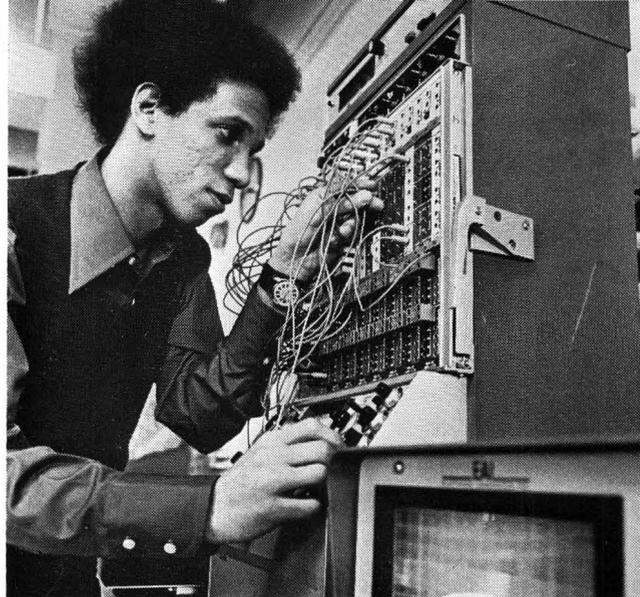
The physical growth in the 1960's was the prelude of discussion about broadening the educational offerings. Until the past decade only degree programs in engineering had been offered. In recent years a discernible interest in related professional career paths has led to viable programs in engineering science, computer science, and industrial management; undergraduate and graduate programs have established in these fields. Other degree programs have been added as well but the deciding factor in the change of name from Newark College of Engineering to New Jersey Institute of Technology was the creation of New Jersey's first public school of architecture as part of NCE in 1973. The new NJIT name became effective January 1, 1975.

Throughout its history the Departmental objectives of its undergraduate curriculum has been to provide a quality education which will enable graduates to either enter the chemical engineering profession directly or alternately, to enter graduate school well-rounded in theory and application. The objectives of the graduate programs have been to broaden and deepen the student's mastery of chemical engineering and related subjects so that he might participate to the fullest extent in the advancement and practice of the chemical engineering profession.

THE FACULTY

DUE TO THE PARTICULAR importance given to the chemical engineering/chemistry department at NJIT, the leadership and faculty support given to its educational effort is especially significant. As mentioned Dr. Joseph Joffe operates as overall chairman with Professor George Keffe as associate chairman of chemical engineering and Dr. Howard Kimmel as associate chairman of chemistry.

It has been largely under this leadership—and during the past ten years—that the department has been able to achieve the national prominence it now has. This period also marked the most dynamic growth in terms of student en-



Process Control simulation on EAI TR 20 Analog Computer.

rollment, faculty growth and physical expansion. More than half of the present instructing staff of chemical engineering joined the faculty in the late 1960s as well as one-third of the chemistry faculty. In addition, Dr. L. Bryce Andersen, dean of academic affairs, and Dr. Wladimir Philippoff, internationally-known rheologist, are members of the chemical engineering department. Most of the teaching staff are professional engineers and have extensive industrial experience.

CHEMICAL ENGINEERING STAFF

L. Bryce Andersen, Vice President of Academic Affairs.

Ernest N. Bart, Fluid Mechanics, Heat Transfer, Mini Computers and Applied Mechanics.

Hung T. Chen, Thermodynamics, Separation Theory (Parametric Pumping), Process Dynamics and Control.

Teddy Greenstein, Low Reynolds Number Hydrodynamics, Biochemical Engineering, Heat Transfer.

Deran Hanesian, Chemical Reaction Engineering, Fluidization, Process Dynamics and Control, Process Simulation and Optimization.

Ching-Rong Huang, Rheology, Biorheology, Biomedical Engineering, Polymerization Kinetics, Catalysis.

Joseph Joffe, Chairman of Department of Chemical Engineering and Chemistry, Thermodynamics (Equations of State, Vapor-Liquid Equilibria, Properties).

George C. Keffe, Associate Chairman, Chemical Engineering, Mass Transfer, Solid Waste Recovery Processes, Photo-chemical Reactions.

Saul I. Kreps, Chemical Reaction Engineering, Catalysis and Catalytic Reactor Design.

John E. McCormick, Computer Applications to Engineering Problems, Applied Mathematics, Mass Transfer.

Wladimir Philippoff, Foundation Research Professor, Rheology.

Angelo Perna, Mass Transfer, Solid Waste Disposal, Air and Water Pollution.

Edward C. Roche, Jr., Process and Equipment Design, Process Simulation and Computer Applications.

Jerome J. Salamone, Assistant Chairman, Chemical Engineering, Non Newtonian Technology, Fluid Mechanics,

Heat Transfer.

Dimitrios Tassios, Applied Thermodynamics (Vapor-Liquid Equilibria), Air Pollution, Technology Assessment.

As one would expect from such a large staff the research interests encompass a broad spectrum. The chemistry faculty, in addition to the standard areas of research, (physical, analytical, inorganic and organic), are conducting research in the areas of water and air pollution, enzymatic removal of pollutants, polymers, biomedical and photochemical induced reactions. Funded research is currently being carried out in the areas of water pollution, blood rheology, hazardous waste disposal and process synthesis. Several NSF undergraduate equipment grants have helped to develop undergraduate laboratory experiments.

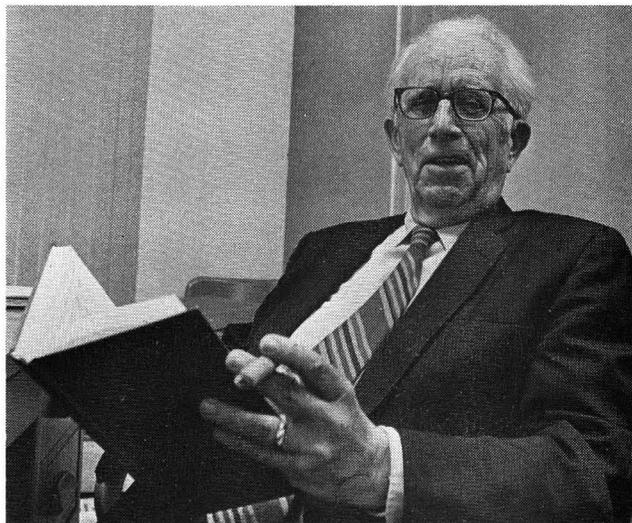
During the past year the members of the department have published 37 papers and presented 23 papers at national and international meetings. Additional activities of department faculty include consulting for the private and public sector as well as reviews for technical journals, and government agencies.

FACILITIES

IN 1969 GROUND WAS BROKEN for the Chemical Engineering/Chemistry complex, (Tiernan Hall) which was completed in 1972 at a cost of \$7 million. The facility was designed as an office, educational and research complex, complete with the latest capabilities for audio-visual instruction. Its four-stories and basement contain a gross area of 140,500 square feet. The basement contains complete machine shop facilities, a modern rheology research lab, a sub-critical nuclear reactor facility, equipment storage area and a student lounge. Instructional classrooms are on the first floor. With the exceptions of two large freshmen lecture halls, classrooms are designed to hold no more than 25 students. The second floor contains all the undergraduate chemistry laboratories. With the exception of department's minicomputer facilities, the third and fourth floors consist completely of research laboratories.

One of the distinctive features of the complex is the undergraduate laboratory facility which includes a four-story high-head area, housing the unit operations laboratory and a separate process dynamics control laboratory. The unit operations facilities consist of separate areas on each floor

interconnected by a high-head area. The basement laboratory area, the largest in square footage, contains experiments related to heat, mass, and momentum transfer as well as several liquid-solid separation experiments. The first floor is basically a solids-fluids area where the drying and fluidized bed experiments are located. The second floor is used for housing experimental apparatus associated with the undergraduate research program and student project studies associated with the unit operations laboratory course. The third floor area contains a reaction kinetics laboratory. The experiments involve a 60 foot tubular reactor, backmix reactors in series, heterogeneous catalysis, surface properties of catalysts, non isothermal batch reactor, and a batch fermentation unit. The fourth floor contains process dynamics experiments in liquid level control, frequency response analysis and on-line reactor temperature controller tuning. Both EAI



George Keeffe, Associate Chairman of Chemical Engineering.

TR-20 and EAI TR-48 analog computers are available. Additional control simulation is provided if desired by an Autodynamics Process Control Trainer.

The laboratory experimental equipment units are essentially of pilot plant size and were recently purchased as part of the department's educational modernization philosophy.

A computation facility includes mini-computers, analog computers and teletypes for the on-campus UNIVAC 3 computer and a State-wide 370/158 IBM System. The analog capability consists of two fully equipped TR-20 machines, with DVM, oscilloscope and x-y plotter accessories and two TR-48 machines. Mini-computer equipment

includes a Wang console and five satellite keyboards, and two programmable 9000 series Hewlett-Packard systems. The 9100A H-P is complete with extended memory, printer and marked paper reader. The newer 9820A unit has two, read only, memory blocks one of which is a math package and the other is a user definable package. Since the unit has a compiler anyone familiar with modern computer programming can rapidly learn to program the unit. In addition, the 9820A is equipped with an alpha numeric printer allowing for convenient formatting of printed statements. Programs for use with the H-P systems are designed and used by students for data reduction in conjunction with experiments in both the unit operations and process dynamics and control laboratories. This equipment is reserved for the use of the faculty and students of the department. The department takes great pride in the facilities and the resulting compliments expressed by visitors from both the industrial and academic sectors.

PROGRAMS

THE UNDERGRADUATE PROGRAM at NJIT has as its goal, an educational balance between technical and non-technical subjects so that the student graduating is not only technically competent, but reasonably sophisticated in social matters. Presently a total of 137 semester hours are required.

The mathematics and physics requirements satisfy ECPD standards and chemistry requirements meet AIChE standards. The chemistry contribution to the undergraduate ChE curriculum is significant in that the courses are designed specifically for the engineering student and are given to engineers by chemists who are colleagues. All the chemistry courses—freshman chemistry, organic chemistry, and physical chemistry—are oriented toward the basic educational needs of a chemical engineer.

Recognizing the need for greater exposure to modern analytical techniques, the chemistry faculty developed a sophomore analytical chemistry program which now will be required by all ChE students. The purpose is to give students the experimental experience in analytical techniques that will be needed in junior and senior laboratory courses.

In the humanities/social and organizational sciences, 27 credit hours are required, providing for non-technical subjects in every semester.

There are five elective and four required courses in this sequence. This requirement is based upon a historic desire at the school to prepare its graduates for corporate management opportunities.

The standard chemical engineering subjects—calculations, process industries, thermodynamics, heat, mass, and momentum transfer, reaction kinetics, process dynamics and control, plant design, and chemical engineering laboratory—provide an additional 39 credit hours and another 9 hours of chemical engineering and technical electives are permitted. The program is more flexible than it seems because of a great deal of freedom in the “technical” and “ChE” electives. A student can use these three courses to develop a solid footing in chemistry, biochemistry, environmental sciences, nuclear chemistry/physics, mathematics/computers, and others as well.

Although the courses on campus reflect the engineering aspects of the institution, a wider variety of liberal arts and life science programs can be considered in conjunction with a neighboring institution, Rutgers-Newark.

Internally, department programs are flexible and can be fitted into fields which include medicine, ecology, law, management, chemistry, process operations, research and design.

The focal points of the undergraduate curriculum are the senior Process and Plant Design course and the senior chemical engineering labora-

The undergraduate lab facility includes a four-story, high-headed area for unit operations lab and a separate process dynamics lab. The former consists of separate areas on each floor interconnected by a high-headed area.

tories. In the Plant Design course the process and equipment design of process units is covered through three basic exercises focusing on process design, equipment design, and process-equipment parameter studies utilizing simulation models. The emphasis of the process design segment is to cover the flow and equipment sequence along with raw materials and location factors. Also the establishment of process operating conditions, material and energy balances, and the evaluation of necessary physical and thermodynamic data. The second segment concentrates on the preparation of preliminary investment and operating cost

estimates, noting the size and/or mechanical designs of equipment, and the utility and instrumentation requirements. The third segment is an exposure to the interrelationships of process and design variables via the utilization of process simulation programs. The course is conducted through a group-oriented workshop atmosphere with written and oral summaries of accomplishments.

The selection of the specific examples for student solution requires some care in that the process must be non-proprietary, basic process data must be readily available, and the scope such that a solution can be obtained within the duration of the course period. With these constraints problems have been formulated in conjunction with various industrial firms, and then used in the process and plant design course. The development of these design problems requires considerable effort, and thus NJIT has actively participated in the case study series as organized by Dr. Buford D. Smith at Washington University (St. Louis, Mo.).

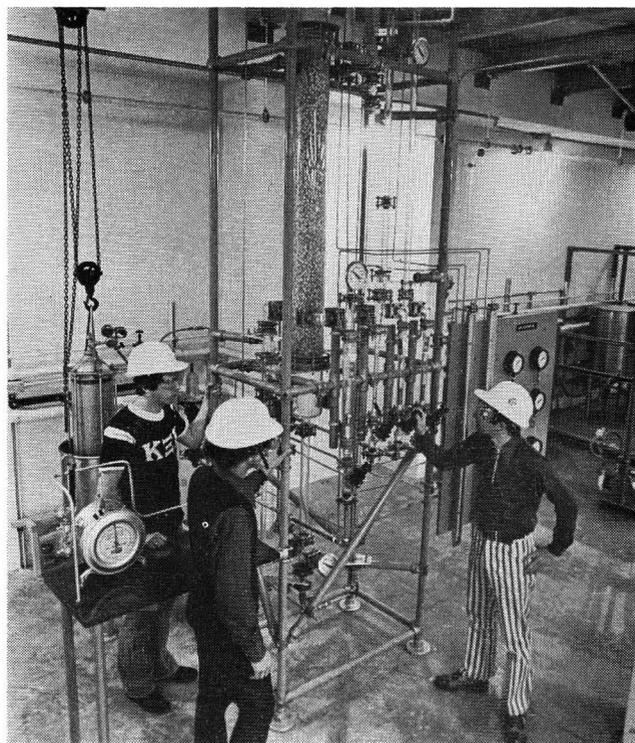
In the undergraduate chemical engineering laboratory, the students are required to complete one experiment in each of the areas of heat, mass and momentum transfer and chemical reaction engineering. The remaining experiments in the two semester sequence are chosen by the students working in groups of three in accordance with their interest and desire for specialization.

The Process Dynamics and Control Laboratory is integrated with the course. Students spend nine weeks on theory and then seven weeks on pilot plant scale control experiments covering liquid level control, frequency response analysis, and on-line, chemical reactor temperature controller tuning for optimum control settings. Analog computations in control are also investigated by simulation of chemical reactions with concentration control by a proportional controller.

On the graduate level, standard master's and doctoral programs are available in chemical engineering. The degree of chemical engineer also available after 24 hours of course work and a minimum of twelve credits for a professional project. Although most of the candidates are part-time evening students, with the number ranging between 80 and 100, the department is concentrating on developing a larger full-time day program. At the present time, there are about 20 full-time master's and doctoral candidates.

The Chemistry Division offers a program lead-

ing to the Master of Science in Engineering Science. The requirements include a minimum of thirty credits which include the option of a six credit Master's Thesis or a three credit Master's Project. Nine course credits are prescribed in the areas of Inorganic, Physical and Organic Chemistry. The remaining credits are electives.



Unit Operations Lab Gas Absorption Experimental Apparatus.

STUDENT-DEPARTMENTAL ACTIVITIES

THE STUDENT POPULATION AT NJIT is basically a commuting one with the problems and attitudes associated with a metropolitan atmosphere. The majority of students hold down part-time jobs to help subsidize their educational and living expenses. Since NJIT is primarily engineering-oriented, there are many demands on a student's time. The department takes pride in its student organizations and in the recognition such societies have received. A close student-faculty relationship is characteristic of the department life. This close relationship has been nurtured primarily by the active student chapters of AIChE (established 1950) and Omega Chi Epsilon (established 1957 as Eta Chapter), and a recently formed Biochemical Club, and has been encouraged by an open door policy on the part of the faculty. □

THE TEXACO-YALE STUDENT CONSULTING PROGRAM

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C. H. WARE, JR.
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Beacon, New York 12508*

THE PRIMARY FUNCTION of an engineering department is to teach students the basic scientific and engineering principles which will become the foundation of their technical knowledge. Since most students will apply this

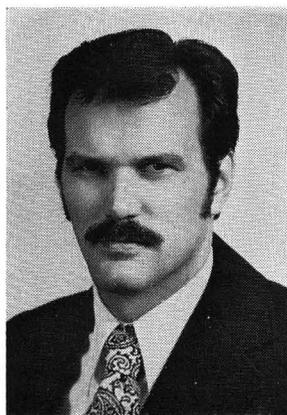
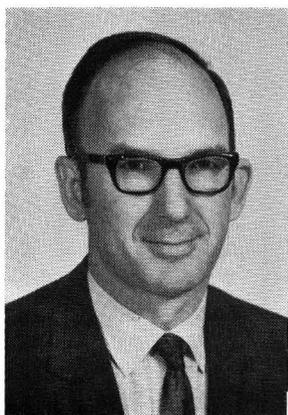
We have tried to create an industrial experience in which students are direct participants rather than observers . . . the vehicle is a set of two or more problems from which a graduate consultant team selects one on which to work full time for one week.

knowledge in industrial jobs, it is important for them, and for the university, to maintain a strong communication link with industry. In fact, weakness of this communication may be the major contributor to the complaint sometimes heard that the attitude of engineering graduate students does not match industrial needs. Summer jobs and cooperative programs provide important industrial experience from which students gain perspective on the importance of various areas of course work and a basis on which to make career decisions. This experience is not available to all students, however. In the following we describe a program which has been designed in a cooperative effort by Texaco and Yale to provide a taste of industrial experience in graduate chemical engineering. Development of the program was spurred by a recent article on the effectiveness of graduate chemical engineering education.¹

Increasing pressure to shorten the time spent in education rules out extensive industrial contact as a general solution to this communication problem. While plant trips and lectures by industrial personnel provide some exposure to the practice of engineering in industry, they are tutorial in nature and may not be readily incorporated into the students "experience." In an attempt to maximize the benefit of a short exposure to industry we have tried to create an industrial experience in which students are direct participants rather than observers.

THE PROGRAM

IN ITS PRESENT FORM, the vehicle for providing this experience is a set of two or more problems supplied by Texaco, from which a team of graduate student consultants selects one on which to work full time for one week. In the first trial run during the summer of 1973, two problems were offered by the Process Analysis Group at Texaco's Beacon Research Laboratories. One problem on catalyst poisoning had received only preliminary attention while the other on design of a laboratory reactor for determination of true reaction kinetics in two phase flow had a tentative solution being tested in the laboratory. A six man student team received the problems on a Friday. The following Monday the group traveled to Beacon for a meeting with Dr. Ware, their Texaco contact. The meeting was devoted to clarification of the problem statement and definition of project objectives. The visit also included lunch with several members of the Texaco staff and a tour of the Beacon Laboratory. On return to Yale, the students chose the reactor design problem (see inset) and over the next three days generated three designs and a written report on their work. The students worked completely independently although both authors were available to answer specific questions. A typed version of the report was mailed to Dr. Ware the next week and a week later he visited Yale to hear oral presentations of



W. N. Delgass did his doctoral work at Stanford University under Professor Michel Boudart. He joined the Yale Faculty as an Assistant Professor in 1969 after a postdoctoral year at the University of California, Berkeley. He is currently Associate Professor of Chemical Engineering at Purdue University. His principal research interest is the study of heterogeneous catalysis by Mossbauer and X-ray photoelectron spectroscopy. (Right)

C. H. Ware, Jr., received his undergraduate education at Princeton University and a PhD at the University of Pennsylvania. He joined Texaco Inc. in 1959, served as Adjunct Associate Professor, Columbia University, and assisted in the development of computer-aided education at the University of Pennsylvania. He recently became an independent consultant. His major interests are new methods for improving and accelerating research/development/design activities. (Left)

the work and discuss the suitability of the solutions to industrial objectives.

While a week is a short time in which to accomplish the stated goals, other student work was suspended and each student spent more than 60 hours in this total immersion effort. In addition to acquiring new chemical engineering knowledge, students had an opportunity to exercise creativity in their approach to the problem and to practice both oral and written technical communication. In this first trial run students received a small consulting fee from departmental gift funds.

STUDENT AND FACULTY RESPONSE

THE STUDENTS WERE ENTHUSIASTIC about the program and felt it a valuable expansion of their experience. Most of them had little previous contact with industry and felt that the visit to the Beacon Research Laboratories and the discussion with Texaco personnel were particularly useful. They were surprised and somewhat uneasy at the generality of the problem statements but particularly as a result of discussions with their Texaco contact, came away with distinct impressions of the depth and scope

of chemical engineering research. Perhaps the greatest new lesson they learned was the preparation of a contingency chart to guide application of a general solution to a specific case. In the beginning the students had a little trouble treating the problem as a job to be done rather than an exercise on which they were being examined. This uneasiness left by the end of the project, however, and the students gained some self-confidence when they found that in a short time in a relatively new area they could generate creative ideas of merit. An unexpected result was the difficulty the students had in organizing for a team effort. The ironing out of initial disagreements gave the students in this group the added benefit of experience in team cooperation.

Both as a new dimension in graduate chemical engineering at Yale and as a means of establishing better communications with industry this program has been a success. The benefit to the students is obvious from their comments. Discussions with Texaco personnel have already revealed several areas in which special lectures or material from Texaco could augment our courses. It is too early to predict whether any joint technical efforts will arise from this association but it seems clear that such a possibility is unlikely without close contact.

INDUSTRY RESPONSE

WHILE THE STUDENT SOLUTIONS are not a finished product, some novel ideas were presented and merit further consideration. The primary solution, use of a stratified packed bed to relax nonidealities, had already been employed by Texaco in a different situation. Other parts of the solution included reactor configurations which had not been tried before. The underlying assumption that experimental design data would be used to aid in formulation of a solution to the problem was also noteworthy. Thus the benefit to Texaco was more than just the satisfaction of making a contribution to education.

As the program is now constructed, presentation of a good problem is crucial. There is a need to balance several important factors:

- problems must be important from an industrial viewpoint
- the time required to prepare a problem statement must not be excessive
- the problems must be broad in scope and amenable to solution by an (imaginative) application of chemical engineering principles (no "trick" problems)
- proprietary information must be protected.

Both as a new dimension in graduate ChE and as a means of establishing better communications with industry this program has been a success . . . while student solutions are not a finished product . . . some novel ideas were presented.

The first factor was taken into account by choosing problems from, or closely related to, current research interests. By choosing the man most familiar with the problem as the industrial contact, the preparation of the problem statement was made easy. Problems considered to date are in the areas of research methodology (eliminating non-ideal flow) or application of the open literature to research problems and decisions. This results in problems having broad scope, usually without using or generating proprietary information.

During the summer of 1974, students received the problems one day before the trip to Texaco. This limits the amount of background they can gather as a basis for asking questions but will leave more time for working on the chosen problem. Since choosing the right problem to work on is such an important component of research, we have sought ways of including experience in this area. We considered presenting a problem, which is not capable of solution because sufficient information cannot be obtained. The time is so short, however, that it is unlikely that students can accumulate sufficient background to identify its insolubility in time to switch to a more fruitful one. An obvious wrong answer also lends an undesirable air of examination to the procedure. We have decided to limit the number of problems suggested to three and, if an insoluble problem is offered, to identify it by the end of the visit to Texaco (second day) to minimize wasted effort.

We look forward to continued development of this program and hope that some of the ideas presented here will be useful to others in strengthening ties between industry and academia.

ACKNOWLEDGMENTS

Development of this program has been made possible by the support of Messrs. Peter L. Paull, Roland A. Beck, Irving D. Pollock and Edward R. Christensen at Texaco and Professor R. W. Wheeler, Department of Engineering and Applied Science, Yale University.

REFERENCES

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STUDENT CONSULTING PROBLEM

Problem Statement

Either

(1) make a recommendation for design and operation of laboratory packed bed reactors for gas-liquid flow, or,

(2) provide a detailed plan of experimental research which would provide the basis for such a recommendation, including the interpretation and recommendation which would be made for each possible outcome of the planned work.

Constraints

Operation must provide for 40-90% conversion of the limiting reactant in the feed.

Two reactor volumes must be covered by the recommendation: 100 cc. maximum, and 500 cc. maximum, representing small and intermediate scale experiments.

Background

Many new petroleum and petrochemical processes are based upon novel catalysts or novel applications of existing catalysts. We will only concern ourselves with catalysts used in packed bed reactors. At the present time there is no way to predict rates of reactions of commercial interest from a knowledge of a catalyst's physical and chemical properties, method of preparation, etc. These rates must be established empirically.

In the normal course of development of an idea from its inception to commercialization, the empirical determination of catalyst performance plays an important role. Included in a typical project is the evaluation of a small quantity of catalyst, usually about 100 cc. and, later, the evaluation of larger quantities, roughly 500 cc. In many processes, reactants are present as liquids and gases at reactor conditions. These so-called mixed-phase operations give rise to non-idealities in the fluid flow which affect the apparent catalyst activity, selectivity and aging rate, the three major performance characteristics. The objective in the design of laboratory reactors and in choosing their operating conditions is, primarily, to eliminate the non-idealities and thus obtain reactor performance which is representative of the intrinsic catalyst behavior. Failing that, the objective would be to provide a sound basis for correcting experimental data to obtain results which are representative of the true behavior. (A non-proprietary literature survey was included). □



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DIAMONDS ARE A THERMODYNAMICIST'S BEST FRIEND

RALPH D. NELSON, JR.
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STUDENTS OF THERMODYNAMICS appreciate having some guide through the thicket of definitions and derivations that usually accompany introductory courses. Numerous sayings and designs have been used over the years (Prins, 1948; Guggenheim, 1949; Burgett, 1972; Marino, 1973; Gangi *et al.*, 1972). I believe that a simple geometric construction is best and here-with submit my candidate for "best of show."

The shape of a square within a diamond is easily remembered, and the working relationships are easily derived. The first law, $dE = dq - dw_{out}$, provides a starting point to fill in the terms. Partial derivatives of the various energies are shown to be equal to nonenergy variables. Partial derivatives of the nonenergy variables are related through crossed partial derivatives of the energies. The diamond is useful because it provides a graphic representation of the relations between basic thermodynamic variables.

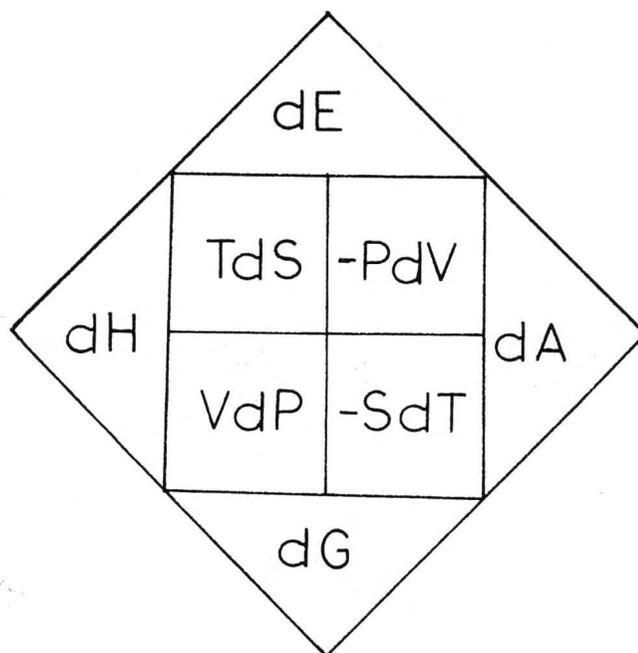
SETTING UP THE DIAMOND

THE FIRST LAW OF thermodynamics states that energy may be converted from one form to another, so that the *total energy flow* into a system is the sum of the various types of energy involved. If the energy flow is due only to heat absorbed, dq , and (piston or shaft) work done by the system, dw_{out} , then $dE = dq - dw_{out}$. A second measure of energy is called enthalpy, H , and is often used when we are dealing with constant pressure systems. The Helmholtz free energy, A , is a measure of maximum work at constant temperature. And the Gibbs free energy, G , is related to chemical reactions and equilibria

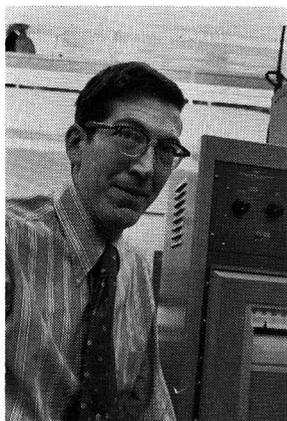
at constant temperature and pressure.

To formalize the relations, draw a diamond with a square inside it, and divide the square into four smaller squares, as shown in the accompanying drawing. In the top three sections, place the definition of total energy flow in terms of heat and work. Place dE in the pointer, TdS (the equivalent of dq here) in the left corner box and $-PdV$ (the equivalent of $-dw_{out}$) in the right corner box. Fill in the remainder of the boxes by "reversing" the terms through the center, so that TdS in the upper left becomes $-SdT$ in the lower right and $-PdV$ in the upper right becomes VdP in the lower left. To fill in the pointers, recall that dH goes next to the heat term TdS (and at constant pressure the other term, VdP would drop out) and that dA goes next to the work term $-PdV$ (and at constant temperature the other term $-SdT$ would drop out). This leaves only one place for dG .

The pointer terms are defined as the sums of the adjacent box terms. The pattern may be



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Ralph D. Nelson, Jr., earned a B.A. in chemistry at Colby College in 1960 and a Ph.D. in chemistry at Princeton University in 1963. Following research and teaching posts at the National Bureau of Standards, Middlebury College, Brown University, and West Virginia University, he earned an M.S.E. in chemical engineering at West Virginia University in 1974. Research into molecular motions in the liquid state has been supplemented by development of time-shared computer applications. He has recently joined the Pigments Department of Du Pont.

inverted, reflected, or rotated to produce the same relationship between the terms. I find this particular arrangement most suitable. Note that the algebraic signs of the terms are explicit and do not depend on the direction of operation, as is the case with other mnemonics. The various energies are defined as changes, so that absolute values for energies are not implied. Burgett's mnemonic "Good Processes Have Several Energy Variables, All Tied," Marion's "SPorTiVe," and Shih-Ching Su's (C.Y. Wen, private communication) "The Gibbs Potential Has Several Exceptionally Valuable Applications" are all present in the diamond's derivative terms.

USING THE DIAMOND FOR DERIVATIVES

THE MAXWELL RELATIONS equate the first partial derivatives of the various energies to nonenergy variables. Only adjacent pointer energies are involved in the Maxwell relations. The procedure should not be memorized, but understood. The definition of each pointer term involves two box terms. Adjacent pointer terms have one box term in common, *e.g.* $dE = TdS - PdV + dA = -SdT - PdV$. The partial derivative of E with respect to V , holding S constant is $-P$, exactly the same result as taking the partial derivative of the adjacent pointer energy with respect to the common box term's

differential variable, holding the uncommon box term's differential variable constant. For this case we get

$$\left(\frac{dE}{dV}\right)_S = -P = \left(\frac{dA}{dV}\right)_T$$

Try working the three others out yourself, comparing them with expressions in standard thermodynamics texts. Maxwell's relations are handy for replacing a term which is hard to evaluate, such as $(dA/dV)_T$, with one which can be evaluated from available data, such as $-P$.

The *Euler relations* result from the inherent equality of the crossed partial derivatives of the energy variables related as shown in the diagram. The result of two successive partial differentiations of energy with respect to the nonenergy variables used in equilibrium thermodynamics is independent of the order in which the differentiations are carried out, *e.g.*

$$\left\{ \frac{d}{dS} \left(\frac{dE}{dV} \right)_S \right\}_V = - \left(\frac{dP}{dS} \right)_V = \left\{ \frac{d}{dV} \left(\frac{dE}{dS} \right)_V \right\}_S = \left(\frac{dT}{dV} \right)_S$$

The pattern may be inverted, reflected, or rotated to produce the same relationship between the terms. The algebraic signs of the terms are explicit and do not depend on the direction of operation.

The result on one side is the partial derivative of the nondifferential variable in a box with respect to the differential variable in an adjacent box, holding the original box's differential variable constant. The other side is the same, except that we start in the adjacent box. Derive the other three yourself for practice. Euler relations may be used to evaluate the changes in one nonenergy variable as a second is held constant and a third is changed. Thus we find that $-(dS/dP)_T$ is the same as $(dV/dT)_P$.

FURTHER ELABORATIONS

THE SCHEME ABOVE IS useful for closed systems, surrounded by walls impervious to

(Continued on page 99.)

PREDICTION OF TEMPERATURE AND OXYGEN DISTRIBUTIONS DURING AEROBIC MICROBIAL GROWTH

STANLEY M. FINGER, THOMAS M. REGAN,
THEODORE W. CADMAN and
RANDOLPH T. HATCH
University of Maryland
College Park, Maryland 20742

AEROBIC DECOMPOSITION IS the basis of many processes which are of current commercial or environmental interest. For example, it is being studied commercially as a means of energy production and has long been used for horticultural purposes such as composting. Environmental examples of aerobic decomposition include various types of waste disposal, strip mine reclamation, and the decomposition of oil spills in the ocean.

Although aerobic microbial growth has been used for centuries, e.g., in composting, it is often practiced more as an art than a science. This is not surprising when one considers the complexity of the biochemical processes by which materials are decomposed. The microorganisms which carry out the decomposition require a suitable environment in terms of nutrients in the substrate, temperature range, oxygen content, and moisture content. In addition, a biochemical source of energy is needed for the decomposition to occur. Thus, in order to develop an accurate mathematical model of the aerobic microbial process it is necessary to consider oxygen transfer into as well as carbon dioxide and thermal diffusion out of the decomposing mass.

DEVELOPMENT OF EQUATIONS

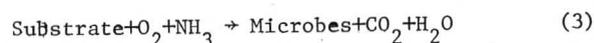
THE THERMAL AND mass diffusion aspects of decomposition are described by Fourier's and Fick's Laws, respectively. When chemical reaction source and sink terms are included, the following equations for the temperature and oxygen distributions result:

$$R = -\frac{k}{H} \frac{d^2 T}{dy^2} \quad (1)$$

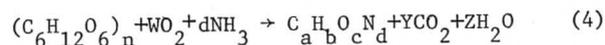
$$-R = -c\bar{D} \frac{d^2 X}{dy^2} + \frac{d}{dy} \left(X \sum_i N_i \right) \quad (2)$$

It is more difficult to determine the mathematical form of the reaction term, R , in Equations 1 and 2, i.e., the rate expression for the complex biochemical reactions taking place during decomposition.

The energy for the numerous biochemical reactions occurring during decomposition comes from the biological oxidation of some of the available carbon.^{1, 2} The biological oxidation of organic compounds to carbon dioxide and water is a complicated process being made up of several successive enzyme catalyzed reactions.³ However, the overall reaction (unbalanced) can be written as



If one considers the substrate to decompose via carbohydrate oxidation a balanced form of Equation 3 can be written



The values of a , b , c , d , W , Y and Z can be calculated from mass balances on the carbon, oxygen and hydrogen. Assuming the composition of cell material to be similar to yeast which is 47% C, 6.5% H, 31% O and 8.5% N⁴ and that about 0.4 g of cell material are produced per gram of substrate, the values of a , b , c and d are: $a = 2.82 n$; $b = 4.69 n$; $c = 1.40 n$; $d = 0.436 n$. Using these

values, a mass balance for the oxygen gives

$W = 3.03 n$, moles CO_2 /mole substrate consumed
 Similarly, mass balances for the carbon and hydrogen give

$Y = 3.18 n$, moles CO_2 /mole substrate consumed
 $Z = 4.31 n$, moles CO_2 /mole substrate consumed

The respiratory quotient (RQ) of a reaction is a measure of the amount of CO_2 produced per unit of O_2 consumed, i.e.,

$$\text{RQ} = \frac{\text{moles } \text{CO}_2 \text{ produced}}{\text{moles } \text{O}_2 \text{ consumed}} = Y \quad (5)$$

The reaction shown in Equation 4 has a respiratory quotient of 1.05. Experimental studies^{5, 6} have measured the respiratory quotient of laboratory compost piles undergoing aerobic decomposition and found that it is approximately 0.9. From this experimental evidence and Equation 5 it can be deduced that the biological oxidation of the substrate is the predominant oxidative reaction taking place during aerobic decomposition. This is not surprising since the other reactions taking place during aerobic decomposition rely upon the biological oxidation to supply the energy necessary for these reactions to proceed. Therefore, in the mathematical model the biological oxidation will be the limiting reaction considered.

Using this model the rate of substrate decomposition according to Michaelis-Menten kinetics (assuming oxygen limitation) is given by the Monod equation:

$$R = \frac{\mu_{\max} (M)X}{K_s + X} \quad (6)$$

Since the reaction rate is assumed to be limited by the rate of oxygen diffusion, $K_s \gg X$, and therefore

$$R = \frac{\mu_{\max}}{K_s} (M)X \quad (7)$$

The temperature sensitivity of μ_{\max} is given by

$$\mu_{\max} = A' e^{-E/R_g T} \quad (8)$$

Substituting this into Equation 7 one gets

$$R = \frac{A'}{K_s} e^{-E/R_g T} (M)X \quad (9)$$

If we further assume that the microorganisms are in a linear growth phase, their concentration

would remain relatively constant and under these conditions Equation 9 reduces to

$$R = A e^{-E/R_g T} X \quad (10)$$

where $A = \frac{A'}{K_s} (M)$. This equation can now be substituted into the transport Equations (1 and 2) to give

$$\frac{d^2 T}{dy^2} = - \frac{AH}{k} e^{-E/R_g T} X \quad (11)$$

$$\frac{d^2 X}{dy^2} - \frac{1}{c\bar{D}} \frac{d}{dy} (X \sum_i N_i) = + \frac{A}{c\bar{D}} e^{-E/R_g T} X \quad (12)$$

According to the model the bulk diffusion term is given by

$$\sum_i N_i \sim N_{\text{O}_2} + N_{\text{CO}_2} \quad (13)$$

But Equation 4 indicates that the oxygen and carbon dioxide are approximately in a state of equimolar counterdiffusion and therefore $\sum_i N_i \sim 0$. This reduces Equation 12 to

$$\frac{d^2 X}{dy^2} = + \frac{A}{c\bar{D}} e^{-E/RT} X \quad (14)$$

Converting Equations 11 and 14 to dimensionless variables gives

$$\frac{d^2 T^*}{dy^{*2}} = - D e^{-B/T^*} X^* \quad (15)$$

where

$$\frac{d^2 X^*}{dy^{*2}} = + C e^{-B/T^*} X^* \quad (16)$$

$$B = E/R_g; \quad C = \frac{AL^2}{c\bar{D}}; \quad D = \frac{AH X_o L^2}{k(T_m - T_o)}$$

The temperature in the exponential term is not made dimensionless since doing so would not simplify the solution of the equations. Equations 15 and 16 can now be solved simultaneously with the proper boundary conditions to get the temperature and oxygen distributions desired.

Aerobic decomposition is being studied as a means of energy production . . . examples include various types of waste disposal, strip mine reclamation, and the decomposition of oil spills in the ocean.

ANALOG COMPUTER PROGRAM

THE ANALOG COMPUTER was chosen to solve this problem since it provided the flexibility to study the effects of changes in the parameters B, C and D as well as give a rapid solution to Equations 15 and 16. The program used to determine the temperature and oxygen distributions is shown in Figure 1. Table 1 summarizes the potentiometer values and amplifier outputs.

The portion of the program in the upper half of Figure 1 is devoted to calculating the forcing function, $e^{(D'-B/T)X}$, where $D' = \ln D$. The value of B, which is related to the activation energy, is controlled by P3. The value of P3 must actually be set at $B/20,000$ in order to get proper scaling. P7 controls the value of the pre-exponential constant, D, and it accomplishes this by being set at the value of $10 e^{(D'-B/T)|_0}$. The output of A6 is $e^{D'-B/T}$ and as can be seen in Figure 1, this is generated by an internal integration loop. This method for generating the exponential function is discussed by Cadman and Smith⁸ and eliminates the problems caused by the use of a non-linear exponential circuit.

The output of A7 is the forcing function, $e^{D'-B/T}X$, which is then integrated twice to get T^* as a function of y^* . Actually the output of the second integrator is $10T^*$ for scaling purposes. In many systems, the temperature and oxygen fluxes at $y^* = 0$ are approximately zero. When this condition is met Equations 15 and 16 indicate that X^* is linearly related to T^* . The linear relationship between X^* and T^* is derived as follows:

$$dX^*/dy^* = - (C/D) dT^*/dy^* \quad (17)$$

$$X^* = - (C/D) \int \frac{dT^*}{dy^*} dy^* + X^*|_0 \quad (18)$$

$$T^* = \int \frac{dT^*}{dy^*} dy^* + T^*|_0 \quad (19)$$

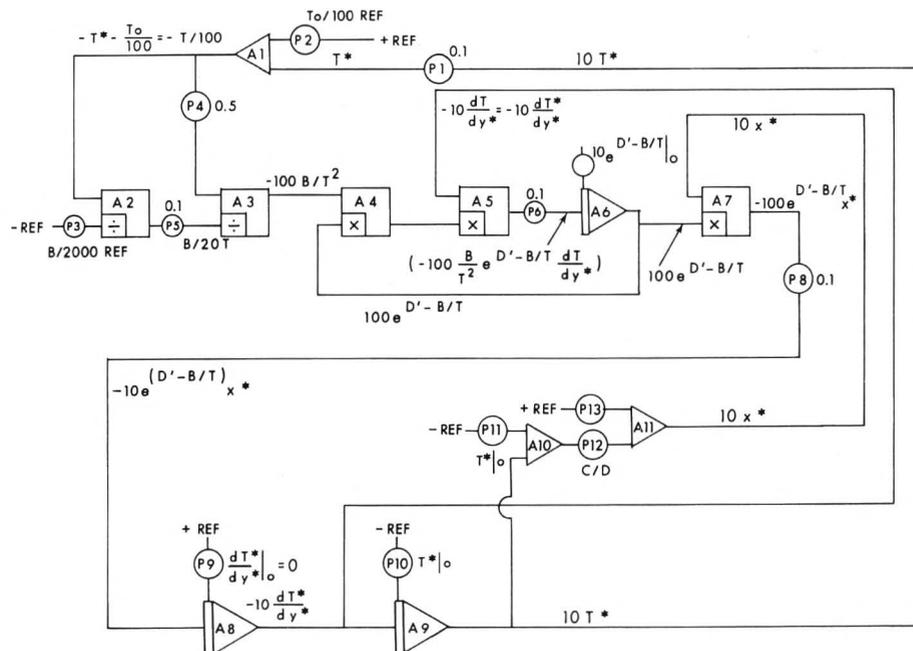


Figure 1: ANALOG COMPUTER SOLUTION

$$X^* = - (C/D) (T^* - T^*|_0) + X^*|_0 \quad (20)$$

$$\text{at } y^* = 0: \quad dT^*/dy^*=0, dX^*/dy^*=0, T^*=T^*|_0$$

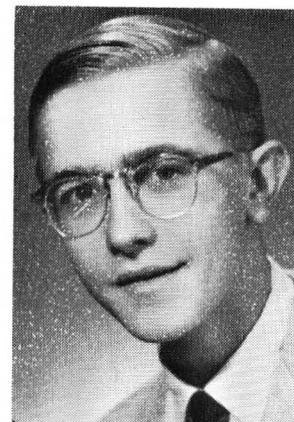
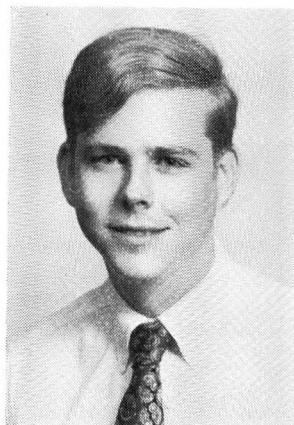
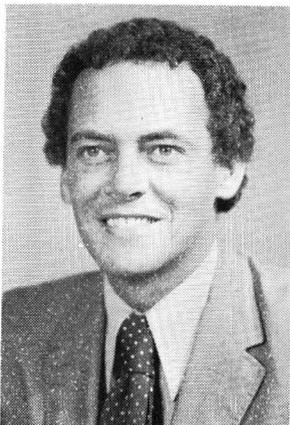
$$\text{at } y^* = 1: \quad X^* = 1$$

This linearity is used to simplify the program by replacing the integrators for X^* with a much simpler circuit and indeed, this is the way in which X^* , or to be more exact, $10X^*$, is generated. P12 controls the value of C/D , P13 controls $X^*|_0$ and P10 and P11 are both set at the value of $T^*|_0$.

In working with the program, the most sensitive parameter has been found to be the exponential part of the forcing function, $e^{D'-B/T}$. The value of B, which is related to the activation energy, can usually be estimated from data in the literature. Thus in fitting experimental data the value of P3 is known independently and the values of P7, P10, P12 and P13 are adjusted to get the best data fit. P11 is set to exactly equal P10 ($T^*|_0$) and therefore is not an independent parameter. P10 and P13 control the values of the boundary conditions, $T^*|_0$ and $X^*|_0$ respectively. Therefore, the computer predictions are essentially controlled by two parameters, C and D, which are controlled by P12 and P7 respectively.

Thomas M. Regan is Director of the Department's Laboratory for Biochemical Engineering and Environmental Studies. His research has been concentrated on mass transfer and some biological and medical applications of mass transfer. Currently, he is on leave and studying human nutrition at Columbia University as a Special Fellow of the National Institutes of Health. Dr. Regan serves as a consultant to industry and government organizations and is a member of AIChE. (Below left)

Randolph T. Hatch is engaged in teaching and research in the field of Biochemical Engineering. Hatch received his BS degree from the University of California, Berkeley and his MS and PhD degrees from the Massachusetts Institute of Technology. He is a member of AIChE, ASM, ACS and serves as the advisor for the student chapter of AIChE. (Below right)



Stanley M. Finger is a Pollution Control Engineer at the Naval Ship Research and Development Center (Annapolis, Md.) specializing in the development of technologies and equipment to eliminate pollution from ships. He is working toward his PhD in ChE at the University of Maryland. He received his MS from the University of Maryland and his BS in chemistry from Pratt Institute. Mr. Finger is a member of AIChE, ACS, Tau Beta Pi, Pi Mu Epsilon and Sigma Xi. (Above left)

Theodore W. Cadman is engaged in teaching and research directed to process control and simulation. He serves as Director of the Laboratory for Process and Simulation at University of Maryland.

Dr. Cadman received his BS, MS, and PhD from Carnegie Mellon University. He is a member of the AIChE, ACS, NSPE and ISA. (Above right)

TABLE 1
Amplifier Outputs And Potentiometer Settings

Component	Output or Value	Estimated Max. Value	Scaled Value
Amp. 1	-T	-400 °K	-T/100
2	B/T	20	B/2T
3	-B/T ²	-0.1 °K ⁻¹	-100 B/T ²
4	$\frac{B}{T^2} e^{D'-B/T}$	0.01 °K ⁻¹	1000 $\frac{B}{T^2} e^{D'-B/T}$
5	$-\frac{B}{T^2} e^{D'-B/T} \frac{dT}{dy^*}$	-0.01	-1000 $\frac{B}{T^2} e^{D'-B/T} \frac{dT}{dy^*}$
6	$e^{D'-B/T}$	0.1	100 $e^{D'-B/T}$
7	$-e^{D'-B/T} X^*$	-0.1	-100 $e^{D'-B/T} X^*$
8	$-\frac{dT^*}{dy^*}$	-1.0	-10 $\frac{dT^*}{dy^*}$
9	T*	1.0	10T*
10	$-T^* + T^* _0$	1.0	$-10T^* + 10T^* _0$
11	X*	1.0	10X*
Pot 1	0.1		0.1
2	T ₀	300	T ₀ /100 Ref.
3	B	6000	B/2000 Ref.
4	0.5		0.5
5	0.1		0.1
6	0.1		0.1
7	$e^{D'-B/T} _0$	0.1	10 $e^{D'-B/T} _0$
8	0.1		0.1
9	$\frac{dT^*}{dy^*} _0$	0	0
10	T* ₀	1.0	T* ₀
11	T* ₀	1.0	T* ₀
12	C/D	10	C/D
13	X* ₀	1.0	X* ₀

RESULTS

THE VALIDITY OF Equations 15 and 16 were tested against available data from compost piles. The boundary conditions used were

$$\text{at } y^* = 0 \quad dT^*/dy^* = 0, \quad dX^*/dy^* = 0, \\ T^* = T^*|_0 \quad \text{at } y^* = 1 \quad X^* = 1$$

where $y^* = 0$ represents the center of the pile and $y^* = 1$ represents the outside surface. The experimental data of temperature distributions in actual compost heaps was supplied by the Butler County Mushroom Farms.† The value for the activation energy was determined from rate versus temperature data on laboratory compost heaps⁵ and was found to be 1.11×10^4 cal/mole. The experimental compost data were then fitted by varying the values of the other model parameters. The shape of the computer was very sensitive to changes in the pre-exponential constants and were affected to a much smaller degree by the boundary conditions.

Correlations between the model and two sets of data are shown in Figures 2 and 3. $y^* = 0$ represents the center of the compost pile with the outside surface being at $y^* = 1$. The temperature range in the two graphs is from 27°C ($T^* = 0$) to 127°C ($T^* = 1$) and the oxygen combination range is from 0% O_2 ($X^* = 0$ to 21% O_2 ($X^* = 1$).

The two sets of data were taken from separate compost piles at a height of 3 feet from the bottom of the pile. The piles were 7 feet wide and approximately 6½ feet high. The computer predictions were within 1°C of the measured temperatures for 9 of the 14 data points, i.e., 64% of the points, and were within 2°C for 13 of the 14 data points. The maximum deviation between the model predictions and the measured temperatures was 3°C. The oxygen distributions predicted are reasonable in that they predict low oxygen concentrations in the interior of the pile, as have been found experimentally^{9, 10} The model further predicts that the oxygen concentration rises rapidly as the outer edge of the pile is approached until at the surface the oxygen concentration is equal to atmospheric conditions ($X^* = 1$ or 21% by volume).

The values of the model parameters used to obtain the computer predictions in Figures 2 and 3 are given in Table 2. The dimensionless parameter C, which is related to the oxygen distribution varies by 7% of the average value for the two data sets, while D, which is related to the temperature distribution, varies by 8% of the average. The relative constancy of the model parameters would be expected since the data were obtained on similar compost piles and therefore only small variations were anticipated.

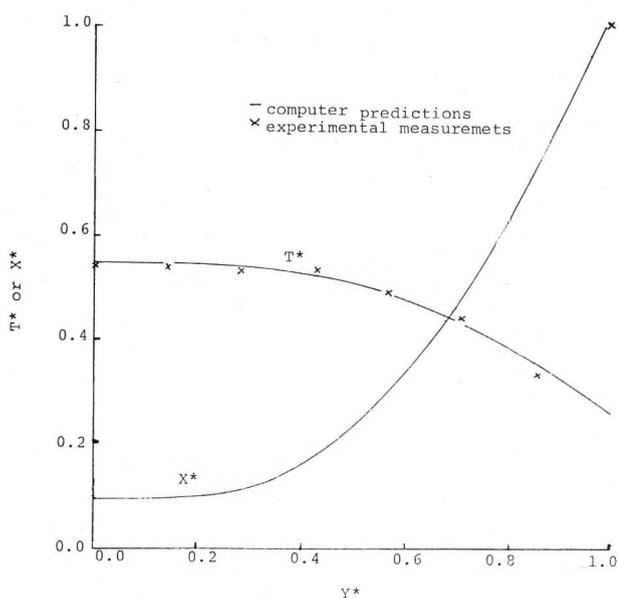


FIGURE 2. Correlations For Compost Heap 1.

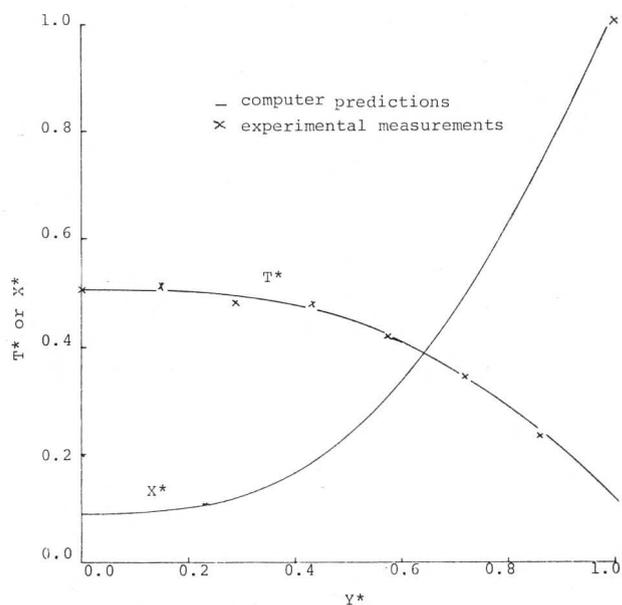


FIGURE 3. Correlations For Compost Heap 2.

CONCLUSION

THE SUCCESS WITH which the model predicted temperature and oxygen distributions gives strong support to the assumptions made in its development. Specifically, proof of the oxygen limitation assumption is very important in commercial activities such as composting since the rate at which the process is carried out could be significantly increased by improved aeration. The mathematical model presented here will be used to study the effects of process modifications to improve such activities. Similarly, the use of the biological oxidation reaction as the predominant oxidative reaction is important in helping to understand and control aerobic microbial growth.

It should also be noted that the basic mathematical form of the model is applicable to any problem in which simultaneous heat transfer, mass transfer and reaction are taking place. The analog computer program that was developed can be adapted to solve the resulting coupled differential equations by simply varying the model parameters and boundary conditions. Although the equations and computer program were developed for a cartesian coordinate system, they could be extended to solve problems in other coordinate systems, e.g., radial distributions in cylindrical or spherical systems. □

(Continued on page 100.)

Today for tomorrow.

AIR POLLUTION: PHYSICAL AND CHEMICAL FUNDAMENTALS

JOHN H. SEINFELD, California Institute of Technology. 1975, 400 pages, \$22.50.

Here is a quantitative and rigorous approach to the basic science and engineering underlying the air pollution problem. The most comprehensive single book available on the subject, it provides an in-depth treatment of air pollution chemistry, atmospheric transport processes, combustion sources and control methods.

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ROBERT V. THOMANN, Manhattan College. 1972, 286 pages, \$18.50.

Using both mathematical models of environmental responses and management and control schemes, the text provides a series of analytical tools for describing and forecasting the effects of the surrounding environment on the water quality of a stream or estuary, presents information on water quality criteria and wastewater inputs, establishes a point of departure for evaluating the worth of water quality improvement projects and discusses the benefits of applying cost/benefit analysis to engineering.

ENVIRONMENTAL SYSTEMS ENGINEERING

LINVIL G. RICH, Clemson University. *McGraw-Hill Series in Water Resources and Environmental Engineering*. 1973, 405 pages, \$17.50. Solutions Manual

While covering a broad spectrum of environmental topics, the focus is on the system as a whole and how its components interact rather than the components themselves. This systems approach is used in formulating and analyzing environmental phenomena, as well as in the selection and design of engineered facilities needed for controlling the environment. Although water environment is considered in greatest detail, also included are air pollution and its control, solid waste management and radiological health. The mathematics of systems analysis and computer solutions is used extensively.

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AIR POLLUTION

H. C. PERKINS, University of Arizona. 1974, 407 pages, \$16.50. Solutions Manual

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A discussion of principles and methods used for testing of gaseous and particulate materials being emitted from industrial, combustion and other sources is presented in this informative text. Organized to give the reader a logical presentation of the steps taken in source testing, the book includes an extensive examination of the equipment, methodology, sampling, and analytical techniques in use for gaseous and particulate particles.

AIR POLLUTION CONTROL: GUIDEBOOK FOR MANAGEMENT

AUGUST T. ROSSANO, JR., University of Washington, and HAL B. H. COOPER, JR., University of Texas at Austin. 1969, 214 pages, \$19.50.

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BASIC ENGINEERING THERMODYNAMICS, Second Edition

MARK W. ZEMANSKY, Emeritus, City College of the City University of New York, MICHAEL M. ABBOTT and HENDRICK C. VAN NESS, both of Rensselaer Polytechnic Institute. 1975, 492 pages, \$16.50. Solutions Manual

Important changes in this revision include a consolidation and unification of material resulting in fewer chapters, the addition of a large number of worked examples, extensive use of SI units, and use of the same sign conventions for both work and heat. Also featured are an expanded treatment of refrigeration and power cycles and extension of the discussion on flow processes to include adiabatic flow processes, especially transonic flows.

METROPOLITAN TRANSPORTATION PLANNING

JOHN W. DICKEY (Senior Author), Virginia Polytechnic Institute and State University. 1975, 550 pages, \$19.50.

While emphasizing the transportation planning process, the contributors to this volume offer an insight into an interdisciplinary approach to solving metropolitan transportation problems. Consisting of engineers and planners, an architect, urban designer and landscape architect, the

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J. M. SMITH, University of California at Davis, and H. C. VAN NESS, Rensselaer Polytechnic Institute. *McGraw-Hill Series in Chemical Engineering*. 1975, 632 pages, \$19.50.

Including a new chapter on solution thermodynamics, the third edition of this successful fundamentals text maintains a unified treatment of thermodynamics from a chemical engineering viewpoint. The chapters on phase and chemical-reaction equilibrium have been rewritten and expanded in order to present a coherent exposition of these topics.

MASS TRANSFER

THOMAS K. SHERWOOD, ROBERT L. PIGFORD, and CHARLES R. WILKE, all of the University of California, Berkeley. 1975, 672 pages, \$19.50.

Compared to the 1952 version *Absorption and Extraction*, this volume is substantially more sophisticated, providing a much broader coverage of mass transfer. Emphasis is on the practical aspects and real problems that demand an understanding of theory. Yet, theoretical derivations are minimized by explicit citation of over 1,100 contemporary references.

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J. ALAN ADAMS and DAVID F. ROGERS, both of the United States Naval Academy. 1973, 480 pages, \$17.00.

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rameters is stressed. Well-documented, interactive computer programs, written in the BASIC programming language, are an integral part of the text.

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By developing principles of kinetics and reactor design and applying them to actual chemical reactors, this text acquaints students with the tools necessary to design new chemical reactors and predict the performance of existing ones. Emphasis is placed on real reactions using experimental rather than hypothetical data.

MASS TRANSFER OPERATIONS, Second Edition

ROBERT E. TREYBAL, New York University. 1968, 688 pages, \$19.50.

The basic approach of this revised text, which treats the major subjects in categories of gas-liquid, liquid-liquid and fluid-solid contact, has been retained as has its application of modern theories and data to practical design of equipment. A major addition to the book includes material on multi-component gas absorption and distillation.

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NELSON LEONARD NEMEROW, Syracuse University. 1974, 353 pages, \$16.50.

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PROCESS MODELING, SIMULATION, AND CONTROL FOR CHEMICAL ENGINEERS

WILLIAM L. LUYBEN, Lehigh University. 1973, 558 pages, \$19.50. Solutions Manual

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THOMAS M. REED and KEITH E. GUBBINS, both of the University of Florida. 1973, 510 pages, \$18.50.

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PRINCIPLES OF NON-NEWTONIAN FLUID MECHANICS

G. ASTARITA, University of Naples and G. MARUCCI, University of Palermo. 1974, 289 pages, \$19.50.

An accessible yet rigorous treatment of non-Newtonian fluid mechanics is provided in this advanced text. Modern continuum mechanics and rheology are presented and developed up to the solution of cases of fluid mechanics problems, particularly for polymeric materials. Along with a consideration of nonlinear thermodynamics, the book offers a critical review and classification of a large number of constitutive equations.

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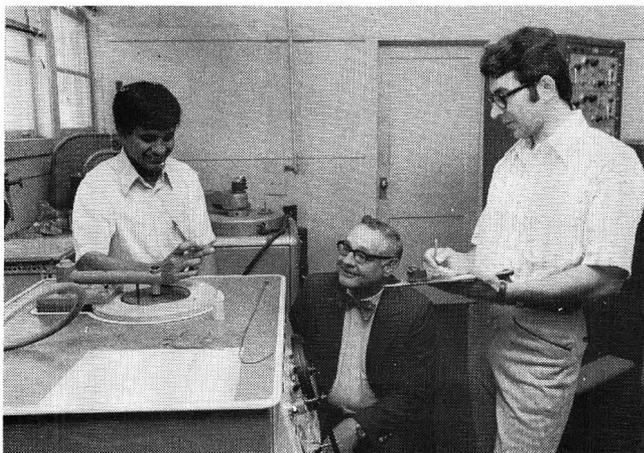


He and his graduate students developed the lab facilities and programs to conduct classical experiments in light and energy scattering . . . These experiments led to fundamental extensions in the theory of energy scattering. This work was . . . cited in the ASEE McGraw Research Award to him in 1958.

and the fundamental behavior of flames. The Flame Dynamics Laboratory has become internationally recognized for its significant contributions to fire research, and recently this laboratory played a major role in evaluating the escape worthiness and occupant survival in automobiles and buses.

Additionally he has directed the program of 20 master's students, 44 Ph.D. students, one Doctor of Engineering student, and is currently serving as committee chairman for five students.

In the 1960s Cheddy became involved in the development and evaluation of a novel process for removal of water from dilute aqueous solutions. This process uses an exchange crystallization technique to take advantage of some unique thermodynamic properties of ice and water. Several patents have been issued on this process in the United States and foreign countries. Currently he is directing the operation of a 75,000 gallon per day demonstration plant which he and his associates designed, developed, and built in Norman for desalinating sea and brackish water. This privately supported pilot plant appears to provide a substantial cost advantage and energy savings over other desalination techniques. It is



He is regarded as the key to LNG technology.

expected that the process soon will be available commercially.

In addition to his academic and public service activities, Cheddy has maintained an active consulting practice. Through his consulting work with Continental Oil Company in Ponca City, he became Director of Research and Engineering. He managed and pioneered the research, development, and implementation of the first commercial process for liquefaction and ocean transport of liquefied natural gas. These original efforts became the basis for the current development of a multibillion dollar industry for the processing, transport, and utilization of LNG. His technical leadership in conjunction with this major effort



Cheddy at home with his wife, Cleo.

has made Sliepceвич an internationally recognized name. He is regarded by many as the father of LNG technology, and in 1962 his contributions were recognized by designation as a National Sigma Xi Lecturer on the subject of "Liquefied Natural Gas—A New Source of Energy."

In 1974 Cheddy Sliepceвич was named Engineer of the Year by the National Society of Professional Engineers, and Oklahoma has recently honored him by inducting him into the Oklahoma Hall of Fame.

Other honors include: The University of Michigan's Sesquicentennial Award for distinguished alumni (1967), membership in the National Academy of Engineering (1972), and Peter C. Reilly Lecturer at the University of Notre Dame (1972). □

DIVISION ACTIVITIES

Continued from page 51.

of ASEE in a miniplenary scheduled for 10:00 a.m., Wednesday, June 18. The panel consists of Ruth S. Stockton, a Colorado State senator, who is on the appropriations committee which has a very strong say over university funding; William K. Coors, a member of the Board of Trustees of the Colorado School of Mines and President of Adolf Coors Company; Brage Golding, president of San Diego State University and previous president of Wright State University and department head of chemical engineering at Purdue University; Neal Pings, vice provost at the California Institute of Technology and chairman of the chemical engineering division of ASEE; and L. Bryce Andersen, Dean of Engineering at the New Jersey Institute of Technology. This is a topic which concerns every educator.

A session at 3:45 p.m. on Tuesday, June 17, which should also attract many non-chemical engineers is one which will consist of progress reports on innovative programs in engineering. Four schools have made extensive changes in the traditional ways of presenting engineering and will discuss the successes and problems they encountered. All of these programs are currently in operation.

The West Virginia Program in design oriented education will be presented by John T. Sears, professor of Chemical Engineering. Wilmer T. Kranich, head of Chemical Engineering at Worcester Polytechnic Institute will discuss their program which replaces course requirements with competency demonstrated by projects and examinations. Ohio University's tutorial program will be explained by Professor Nicholas Dinos of the chemical engineering department. This program is based on the Oxford Cambridge Tutorial concept, and is for exceptional students. The final presenter will be Professor Clyde H. Sprague, Coordinator of Engineering at the University of Texas of the Permian Basin. This new university is operating all their engineering courses on a self-paced basis.

The theme of the 1975 convention is "Engineering Education for World Development." On Wednesday at 1:45 p.m. there will be four papers given at a session entitled, "How Should Chemical Engineers Train Foreign Students from Developing Countries." Speakers from the University of Kansas, Toledo, Pittsburgh, and Mis-

souri will discuss how they have changed traditional programs to make them more useful to foreign students when they return to their own countries. They will discuss how to give them more managerial, practical knowledge, and laboratory skills.

A panel of experts will convene on Monday, June 16 at 4:00 p.m. to inform you what a department head can do to obtain research funds for new faculty members. They should be able to tell us how all our departments can obtain five digit research grants for inexperienced proposal writers.

The 3M award lecture which is always a highlight of the meeting will be given at 1:30 p.m. on Tuesday, June 17. The speaker had not been selected at press time.

Have you ever wondered what your legal and moral obligations are if you are called as an expert witness in a trial? Can a lawyer twist you around his thumb? The meeting scheduled for Wednesday, June 18, at 3:45 p.m. and entitled, "Law, Technology, and the Role of the Expert," should provide you with the answers.

If this is not enough, the division also is sponsoring the annual banquet on Tuesday night. It features a presentation by Robert Ferguson, Dean of Engineering at the University of Idaho. He will talk about his experiences in Ecuador and Peru. Bring your wives to this one.

There is also a business luncheon on Wednesday which all should attend so that you may shape the future of your society.

ChE news

NEW CHEMICAL ENGINEERING DEPARTMENT HEAD AT THE UNIVERSITY OF ARIZONA

Dr. Joseph F. Gross has been appointed new Head of the Chemical Engineering Department at The University of Arizona. Dr. Gross succeeds Dr. Don H. White, the founding Head of the Department, who stepped down last year to devote more time to teaching, research and University/industry relations. The Department searched nationwide and then elected to reach into its ranks for the new Head.

Dr. Gross came to The University of Arizona in 1972 from the Physical Sciences Department of the Rand Corporation in Santa Monica, California.

Dr. Gross was educated at Pratt Institute in Brooklyn, New York, and at Purdue University, West LaFayette, Indiana. In 1957, he was a Fulbright Scholar in Germany. He has published over fifty technical papers and holds membership in several learned and professional societies.

TUBULAR FLOW OF PSEUDOPLASTIC FLUIDS

CHARLES B. WEINBERGER
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Philadelphia, Pennsylvania 19104

IN THE FLOW OF POLYMER melts, one of the most striking phenomena commonly observed is pseudoplastic behavior or the decrease in apparent viscosity with increasing rate of shear. Although certainly a majority of chemical engineers will encounter such behavior at some point in their careers, the chemical engineering undergraduate's exposure to such effects is usually limited to one, or perhaps two, problems in a course in momentum transport. In the experiment described below, we at Drexel University have attempted to deepen the student's exposure to this, and other, interesting aspects of the flow of polymeric fluids.

The experiment consists of measuring the rates of drainage, by gravity, of a non-Newtonian fluid from a tank through vertical tubes of various lengths and diameters. These measurements, plus that of the overall head—distance between the fluid surface and the tube exit, permit the student to determine the material constants K and n in the familiar power-law equation:

$$\tau = K |\dot{\gamma}|^{n-1} \dot{\gamma}, \quad (1)$$

where τ and $\dot{\gamma}$ are the shear stress and rate of shear, respectively.

Although the experiment appears straightforward, the analysis of the data contains an interesting twist, arising from determination of the frictional losses in the tube. Except for a small kinetic energy correction, the overall frictional losses simply equal the read loss; but the overall frictional losses consist of those in the tube and "other" losses. For many non-Newtonian fluids these "other" losses are of the same order of magnitude as those in the tube and thus cannot be neglected. Most of these "other" losses occur in the region of converging flow upstream of the tube entrance¹ although those associated with velocity rearrangement at the tube exit and in the tube's entrance region also contribute.²

The origin of these converging-flow losses can be explained qualitatively by the fact that at least some polymeric solutions possess a much higher "extensional viscosity" than shear viscosity, and upstream of the tube entrance, the motion is predominantly an extensional deformation. For these solutions, then, the converging-flow losses can be several orders of magnitude greater than those for a Newtonian fluid of comparable shear viscosity.

The student, therefore, is introduced to the phenomena of pseudo-plastic behavior and high converging-flow losses. In addition, the experiment itself parallels an instrument used widely in industry, the capillary viscometer. Finally, the data analysis illustrates clearly the use of both the mechanical energy balance equation and the quasi-steady state approximation.

THEORETICAL

MOST STUDENTS SELECT as their objective the determination of the power-law constants of the particular fluid used. For this objective, they need to determine the apparent viscosity, μ_{app} , or the local ratio of shear stress to



Charles B. Weinberger completed his undergraduate work at the University of California and his graduate work at the University of Michigan (PhD, 1970), all in Chemical Engineering. His industrial experience ranges from studies of wheat-peeling and mass transfer and thermodynamic characteristics of molten salts to polymer processing—the latter with DuPont (1970-72). He joined Drexel University in 1972. His current teaching and research interests are in the areas of polymer processing, rheology, and fluid mechanics.

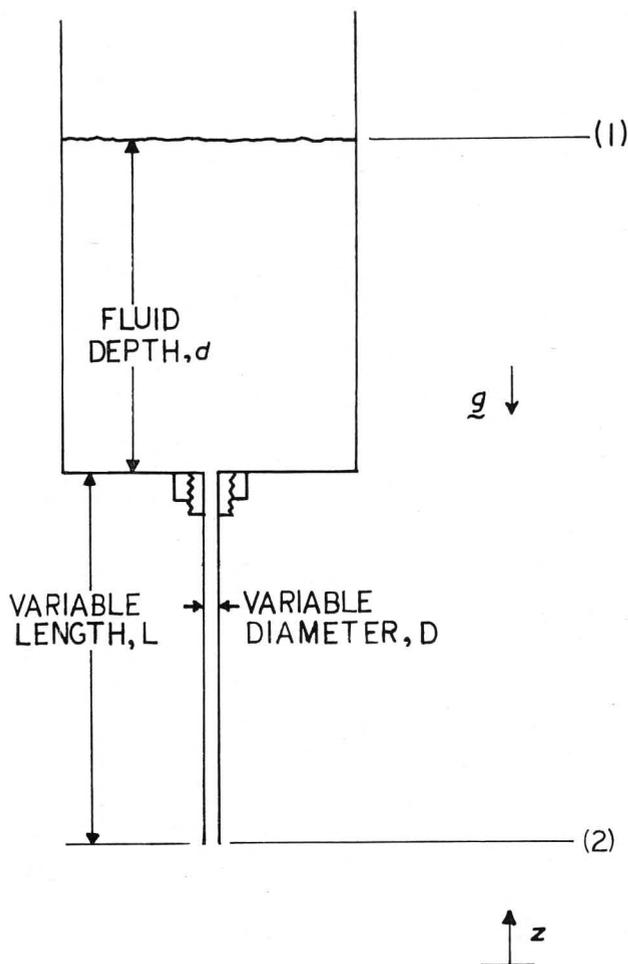


FIGURE 1. Sketch of Apparatus.

shear stress to rate of shear, $\tau/\dot{\gamma}$. Since

$$\mu_{app} = K |\dot{\gamma}|^{n-1} \quad (2)$$

the dependence of apparent viscosity on shear rate for $n \neq 1$ is immediately obvious.

The first step, then, is to determine the shear stress at the walls of the tube, τ_w . To do this, a mechanical energy balance is taken over surfaces (1) and (2) of Fig. 1. The quasi-steady state approximation is applied, thereby eliminating the unsteady-state term (the student can easily perform a quick numerical computation to check the validity of this approximation). The pressure terms cancel and the kinetic energy at surface (1) is negligible, leaving:

$$\frac{\overline{u_2^3}}{2 u_2} + g (z_2 - z_1) + lw_t = 0 \quad (3)$$

For the fluid we use, the first term of Eq. (3), the kinetic energy term, is less than 10% of the other terms; thus, an assumption of a parabolic

velocity distribution in the tube introduces an error of less than 1% in lw_t . As mentioned earlier, the total lost work, lw_t , includes both frictional losses in the tube and "other" losses, $lw_t lw_o$, respectively. lw_t is the tube frictional loss exclusive of extra losses associated with velocity rearrangement in the tube's entrance region, or:

$$lw_t = \left(\frac{dp}{dz} \right)_c \frac{L}{\rho} \quad (4)$$

where $\left(\frac{dz}{dp} \right)_c$ is the equivalent pressure gradient

downstream of the entrance region and L is tube length. lw_o can be estimated by forming a Bagley-type plot³ that is, by determining the ordinate intercept on a plot of lw_t versus tube length, keeping diameter and flow rate constant. For an inelastic non-Newtonian fluid (only approximated by the fluids we use) lw_o includes viscous losses in the converging section and at the tube exit, as well as the extra losses in the tube's entrance region associated with developing the velocity profile in the tube. For the fluids that we use, lw_o consists primarily of converging-flow losses; for the student to confirm this, however, he must go to the literature to find means to predict the magnitude of the other terms.

The friction loss in the tube is then determined by difference,

$$lw_t = lw_t - lw_o \quad (5)$$

From a second mechanical energy balance and a momentum balance on the fluid in the tube, the wall shear stress is

$$\tau_w = \frac{\rho D lw_t}{4 L} \quad (6)$$

The second step is then to determine the shear rate at the wall $\dot{\gamma}_w$, one procedure is to use the Weissenberg-Rabinowitsch-Mooney equation:

$$\dot{\gamma}_w = 3/4 \phi + 1/4 \tau_w \frac{d\phi}{d\tau_w} \quad (7)$$

where

$$\phi = \frac{32 Q}{\pi D^3} \quad (8)$$

The derivation of Eq. (6) is described verbally and the derivation is left to the student. (An interesting pedagogical benefit of the derivation of Eq. (6) is the necessity to use Leibnitz's formula.⁴ A plot of τ_w versus ϕ , along with Eq. (7),

yields $\tau_w(\gamma_w)$ and thus $\mu_{app}(\gamma)$, (Note that τ_w should depend only upon tube diameter, not length.) This procedure, since it relies on locally differentiated data, is subject to considerable data scatter. Such scatter can be minimized by assuming the existence of a power-law fluid, for which

$$\tau_w = K' \phi^n \quad (9)$$

where the relationship

$$K = K' \left(\frac{4n}{3n+1} \right)^n \quad (10)$$

can be derived from Eq. (6). By plotting $\log \tau_w$ versus $\log \phi$, the constants K' and n , and thus K and n , can be obtained.

EXPERIMENTAL

The draining tank is cylindrical, 31 cm high and 20 cm in diameter; copper tubes, ranging in diameter from 0.3 to 0.8 cm and in L/D from 11 to 110, have screw fittings for easy attachment and removal from the tank. A screen, placed two cm above the tube entrance inhibits vortex formation. Flow rates are measured by catching and weighing the fluid issuing from the tube in a measured period of time.

The fluid consists of 0.5 wt% Separan AP30, a high-molecular weight polyacrylamide obtained from the Dow Chemical Co., dissolved in a 1:2,

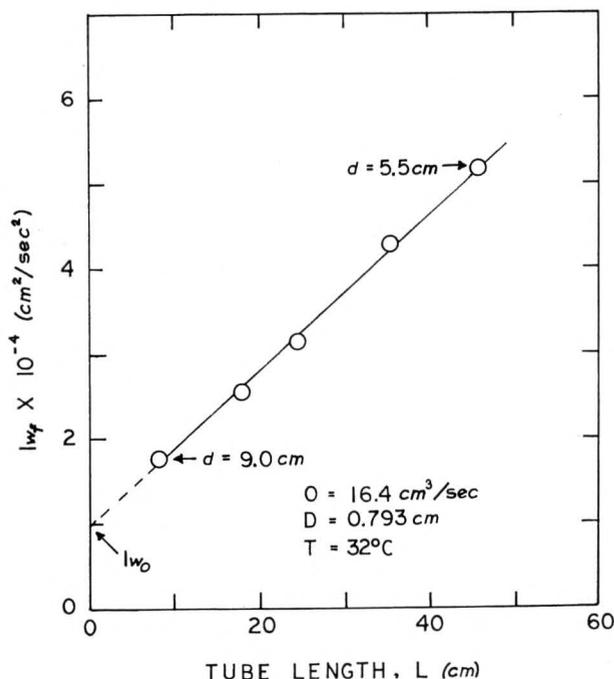


FIGURE 2. Determination of "other" Frictional Losses, lw_o , As the Ordinate Intercept.

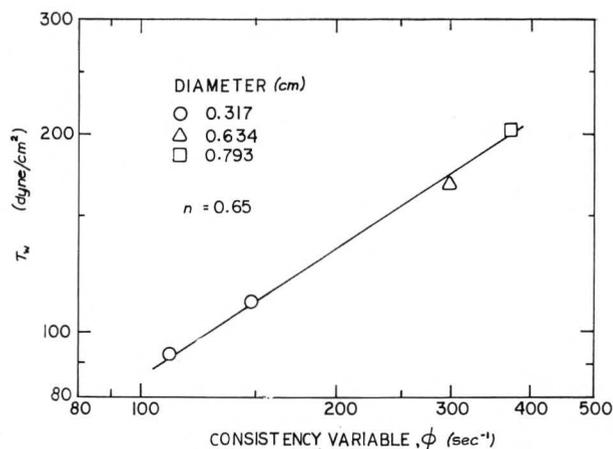


FIGURE 3. Flow Curve in Terms of Consistency Variables.

by weight, glycerol-water solvent. Results with a lower concentration of polymer, 0.25 wt%, were unsatisfactory because effects of the solution's elasticity precluded accurate estimation of lw_o , and thus lw_t . Of course, other polymer solutions could also be used; we note that aqueous solutions possess the advantage of being easy to clean up.

For each diameter the overall head, Z_1-Z_2 , required to maintain a given flow rate is measured for various tube lengths. Recall that Q must be kept constant as L is varied in order to determine lw_o , which depends upon Q and tube diameter. The fluid depth in the tank should be kept sufficiently large so that lw_o does not depend on this depth. The necessary experimental trial and error procedure required to maintain Q constant (quasi-steady-state) is rather simple. A plot of lw_t versus L for each tube diameter extrapolated to zero tube length then yields lw_o ; an example is shown in Fig. 2. These losses can be compared to the entrance-region losses for Newtonian fluids in laminar flow.⁵

Once the extra losses have been determined, τ_w can be calculated from Eq. 3, 4 and 5. Assuming the applicability of a power-law fluid model, $\log \tau_w$ is plotted versus $\log \phi$, as shown by Fig. 3; this plot yields the values $n=0.65$ and $K'=4.25$ dyne-secⁿ/cm². From Eq. 10, $K=3.91$, and thus

$$\mu_{app} = 3.91 |\dot{\gamma}|^{-0.35}$$

OTHER EXPERIMENTAL OBJECTIVES

THE STUDENT IS ENCOURAGED to select his own experimental objective and the flexibility of the draining-tank apparatus permits the pursuit of several other objectives. In addition to the traditional analysis of an unsteady

flow situation, two such studies include:

- Dependence of converging-flow losses upon flowrate and tube diameter,
- Using only water, comparison of entrance-region pressure drop with that of fully developed flow as a function of Re and L/D for turbulent flow of water in circular tubes.

The first study permits a prediction of the dependence of the first normal stress difference on shear rate [1].

SUMMARY

In any laboratory experiment, the chemical engineering educator is most interested in the specific teaching values of the experiment. In this particular experiment, there are several. First, the student gains valuable practical experience with several analytical concepts—specifically, momentum and mechanical energy balances, Leibnitz's formula, and the quasi-steady state approximation. Second, the apparatus simulates an instrument used widely industrially, the capillary viscometer. Finally, the experimental apparatus, which is simple to operate and yields accurate results, illustrates such complex non-Newtonian flow behavior as shear-thinning viscosity and high

viscous losses in converging flow.

NOMENCLATURE

d	depth of fluid in tank, cm
D	tube diameter, cm
K, K'	material constants in power-law model, $\frac{\text{dyne-sec}^n}{\text{cm}^2}$
L	tube length, cm
lw	lost work, cm^2/sec^2
n	material constant in power-law model, dimensionless
p	pressure
Q	volumetric flow rate, cm^3/sec
u	velocity in axial direction
z	distance coordinate
	Greek Letters
γ	rate of shear, sec^{-1}
μ	viscosity, P
ρ	density, gm/cm^3
τ	shear stress, dyne/cm^2
Φ	consistency variable, sec^{-1}

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IDENTITY, BREADTH, DEPTH IN A COOPERATIVE PROGRAM

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EARLY IN THE HISTORY of Chemical Engineering at Waterloo it became apparent that the popularity of the Cooperative Programme would cause the department to become quite large and, in so doing, provide many good opportunities for innovation in curriculum development.

Firstly, there was the opportunity to offer a wide variety of specialist courses. In addition, a concentrated technical and non-technical curriculum was possible because the cooperative work terms would provide the practical experience needed by the chemical engineering undergraduate. In developing such a curriculum in a very short time there was the danger that it would lack cohesion and purpose. Also the departmental size and the inevitable on-off discontinuity of the cooperative system could cause the students to have a lack of identity. The Waterloo programme was developed to exploit the advantages and to anticipate and avoid the disadvantages.

COOPERATIVE ChE PROGRAM

One hundred and twenty first-year students enroll in September of each year in Chemical Engineering. (This is in contrast to the approximately five hundred other engineering students who enroll in General Engineering. One other department, Systems Design, also enrolls into its first year programme.) One advantage of a first year chemical group is to provide a sense of identity for the students, who are often lost in the vastness of a large university and need "to belong." The effects of this identity advantage are intangible, but there are a few indications: for example, in the level of the ChE mathematics marks which more often than not are higher than the rest of engineering, which takes exactly the

same course. Certainly the ChE first year students get to meet and know their professors early in their first term. For example in September of 1974 the ChE class is being taught in one way or another by at least ten ChE faculty members. In this 1A term the students receive the same Mathematics, Chemistry and Physics (see Table I for curriculum content) courses as the rest of engineering. In addition, they obtain a course in Measurement and a course given by and for Chemical Engineers, namely, "Introduction to Engineering Concepts I" which is an introduction to the basic methods and principles used by engineers in the analysis and design of physical processes. Topics covered by means of lectures, case studies and problem assignments are: units, dimensions, measurements, mass balance, behaviour of fluids, non-technical and social implications of the engineers work, freehand sketching and blueprint reading. One non-technical elective can also be selected from a choice of three specially designed for the freshman student.

In January, the ChE class divides and one stream goes to industry while the other (1B class) continues for a second term of studies. This streaming has the advantage of reducing the class size, and ensuring the subsequent year-round use of the university physical plant and teaching resources. The courses taught during this term are again general to all of engineering except, "Introductory Engineering Concepts 2" which extends the topics covered in the previous course to include energy balances, unsteady state behaviour of engineering systems, and laboratory experiments to illustrate the physical principles discussed.

In the term beginning in early May, the students who were in industry return for their 1B term and the group which has already taken the 1B term now moves out into industry. Thus, the classes alternate with terms on-campus and terms

TABLE I Curriculum of the 1974 Freshman

1A Fall 1974	1B Winter and Summer 1975
Introductory eng. concepts	Introductory eng. concepts cont'd.
Calculus 1	Calculus 1 cont'd.
Algebra 1	Algebra 1 cont'd.
General Chemistry	Digital Computation
Mechanics	Electricity and Magnetism
Topics from scientific thought	
Introduction to the sciences of man	One of these courses in each term
Topics from the arts and humanities	
2A Fall and Winter 1975-76	2B Summer and Fall 1976
Calculus 2	Differential equations
Statistics	Transport processes 1. Fluids
Organic chemistry 1	Organic chemistry 2
Physical chemistry 1	Physical chemistry 2
Inorganic chemistry 1	Physical chemistry lab.
Non-technical elective	Non technical elective
3A Winter and Summer 1977	3B Fall and Winter 1977-78
Applied mathematics	Chemical engineering laboratory
Transport process 2. Heat transfer	Transport processes 3. Mass transfer
Inorganic chemistry 2	Chemical reaction engineering
Instrumental methods of chemical analysis	Technical elective
Chemical engineering thermodynamics	Non-technical elective
4A Summer and Fall 1978	4B Winter 1979
Process dynamics and control	Research-design project or
Engineering economics	Process systems design or
Process design and technical seminar	Technical elective project
Technical elective	3 Technical electives
Technical or non-technical elective	Technical or non-technical elective

in industry until they combine again in the final 4B term before graduation. Table I shows the curriculum facing the 1975 Freshman and the way in which he is expected to progress through the B.A.Sc. programme.

Some special features are contained in the programme which reflect the earlier discussion of our concern with the advantages and disadvantages associated with the large department.

- Each student can select from six to eight technical

elective courses at least three of which must be taken from an option package (see below for details). Breadth and depth!

- The undergraduate student has the opportunity to select from four to six non-technical courses from offerings across the whole university. Breadth!
- A set of seven mathematics courses culminating in a course in "Applied Mathematics" (3A Term) are core content of the programme. Depth!
- A set of three transport processes courses and one chemical engineering laboratory is core content. Depth!
- Chemical engineering thermodynamics, instrumental methods, chemical reaction engineering, process dynamics and control, engineering economics and technical seminar are all core courses. Breadth!

TECHNICAL ELECTIVES

Five to seven Technical Elective courses must be selected by the undergraduate. To ensure each student obtains a reasonably deep understanding of at least one area of interest, a minimum of three courses must be chosen from one of the option groups listed in Table II. These course groupings reflect the main interests of the faculty members in the department. The other technical electives may be chosen from other ChE offerings or from other science, mathematics or engineering courses offered within the university provided the associate chairman of the department approves.

GRADUATE COURSES

M.A.Sc. THESIS STUDENTS must take at least four graduate courses at least half of which must be taken from the list shown in Table III. Course work M.A.Sc. students must take eight courses and write an Engineering Report.

Early in the history ChE at Waterloo it became apparent the popularity of the Co-Op program would cause the department to become quite large, and provide many good opportunities for innovation in curriculum development.

Ph.D. students must take at least a further four courses beyond the M.A.Sc. requirement and in addition must pass the Research Proposal exam and defend a Ph.D. thesis. The Graduate course programme of the department fits again into the group pattern and students in collaboration with

their supervisors may plan a personalized curriculum which will provide them with depth of knowledge in their own special area of interest and breadth of knowledge of some of the latest developments in the field of ChE generally.

TABLE II Undergraduate Technical Electives

1. **Transport Processes**
 Selected topics in process applications
 Physico-chemical properties of gases & liquids
 Air Pollution
 Non-Newtonian flow and heat transfer
2. **Mathematical Analysis and Control**
 Chemical engineering analysis
 Process dynamics and control 2
 Process control laboratory
3. **Polymer Science and Engineering**
 Introduction to polymer science
 Physical chemistry of polymers
 Polymer laboratory
4. **Extractive and Process Metallurgy**
 Introduction to extractive metallurgy
 Metallurgical chemistry
 Principles of high temperature extractive metallurgy
5. **Biochemical and Food Engineering**
 Introduction to biochemical engineering
 Fermentation operations
 Food processing
6. **Pollution Control Engineering**
 Selected topics in process applications
 Air pollution
 Introduction to biochemical engineering
 Water pollution
7. **Research and Design**
 Research-design project 1
 Research-design project 2
 Process systems design
 Technical elective report
8. **Non-Technical**
 The Chemical Engineer as an Entrepreneur

MOST RECENT DEVELOPMENTS

RECENTLY THE PROVINCE of Ontario has been assessing all the Ph.D. programmes offered in the Provincial Universities. The Waterloo doctoral programme and its plans for the coming years was approved by the external consultants, however, a general recommendation was that "Ph.D. programmes in addition to the usual scholarly goals, have as one of their aims an effort to develop entrepreneurship in students since this is a quality so badly needed at present in Canada." At Waterloo we have taken this as a challenge and we have prepared a course entitled, "The Chemical Engineer as Entrepreneur." The course

will be available to 4B undergraduates and graduates. "Engineering Economics" or its equivalent will be required as a prerequisite. The course is intended as an elementary introduction to the mechanism by which an individual may develop a small business for the purpose of supplying goods or services to the chemical or resource processing industries. The view presented is that of an individual engineer who must perform most of the technical and management functions himself, with the occasional help of professional specialists, rather than that of new enterprise management as practiced by large corporations. The main purpose of the course is to give a familiarity with the problems and methods of launching in Canada a new small enterprise in the chemical technology field. Technical, economic, legal and financial aspects will be outlined over a broad spectrum of topics. The proposed course has generated enthusiasm among many undergraduates and graduates and expected enrollments are high.

Curriculum development is a continuous process at Waterloo. Many iterations have been made for the curriculum to reach its present form

A general recommendation was that, "Ph.D. programs in addition to the usual scholarly goals, have as one of their aims an effort to develop entrepreneurship in students since this quality is so badly needed in Canada" . . . we have taken this as a challenge.

in just a few years. Usually new ventures are first discussed at the Departmental Curriculum and Graduate Review Committee levels. Each of these committees contain active student representatives. Changes are less frequent now than they were three or four years ago and when they are made, questions such as whether or not they add breadth or depth to the programme or whether they can provide the student with a greater sense of identity with his chosen career and department, are of paramount importance.

The last word on the curriculum is given to students who have been through it all!

STUDENTS VIEWPOINT

Peter Douglas and Gordon Hayward (Class of '74)

"Like any first year students, the ones at Waterloo

TABLE III Graduate Courses

1. **Transport Processes**
 - Theory and applications of transport phenomena
 - Behaviour and properties of particulate material
 - Statistical theory of matter
 - Special topics in transport processes
 - Selected applications of the statistical theory
2. **Mathematical Analysis and Control**
 - Process optimization
 - Advanced mathematics in engineering research
 - Statistics in engineering
 - Chemical reactor analysis
 - Selected topics in analysis of chemical processes
 - Heat and concentration waves
3. **Polymer Science and Engineering**
 - Principles of Polymer Science
 - Physical properties of polymers
 - Polymer synthesis and characterization
 - Solution properties of macromolecules
 - Selected advanced topics in polymer science and engineering
4. **Extractive and Process Metallurgy**
 - Applied physical inorganic chemistry
 - Hydrometallurgy
 - High temperature metallurgy
 - Special topics in hydrochemical metallurgy
 - Special topics in high temperature metal extraction
5. **Biochemical and Food Engineering**
 - Principles of biochemical engineering
 - Advances in biochemical engineering
 - Special topics in biochemical engineering
6. **Research and Design**
 - Oral exam for the Ph.D.
 - Research proposal for the Ph.D.
 - Graduate research seminar
 - Engineering report for the course work M.A.Sc.
 - Thesis for M.A.Sc.
 - Thesis for Ph.D.
7. **Non-Technical**
 - The Chemical Engineer as an Entrepreneur

initially find themselves a little lost or confused and overburdened with work in their new environment. With the ChE class smaller and separate from the other engineering disciplines the first year students are usually a more closely-knit group which is helpful. In addition, the ChE faculty (28) make themselves very approachable to the students. This is encouraged with "coffee and donuts talk sessions," and class professors assigned to first year classes. Class professors act as resource persons, counselors, and motivators. Sometimes they give a few lectures. For example, ours spent time teaching us speedy slide-rule pushing. Generally, the first two years of the programme included many courses in the fundamentals of chemistry, physics and mathematics. Looking back over the years, we remember these courses to have been uninteresting because they seemed to lack apparent ties to practical applications. For this reason, these first two years were probably the most difficult for us. A major improvement

now has more ChE professors teaching first and second year courses. An introduction to ChE through a programme provided for interested high school students in which first and second year students participate also helps relate pure science and math to ChE problems [1].

In the third and fourth years, heat, mass and momentum transfer are taught. In addition, the student may choose technical electives and begin to specialize in the specific area of his choice. We choose both the transport and control options hoping that we would be better suited to a variety of chemical industries rather than just the polymer or food industry. In the fourth year the student is required to work on either a research or design project and is able to effectively apply many of the tools which heretofore (in his academic career) have been limited to text book problems. The research projects provide for specific interests beyond the scope of the other electives. In this way, one of us studied turbulent heat transfer in a wind tunnel, a project which is rather unconventional for chemical engineers.

Aside from academics, the co-op programme plays an important role in the development of a chemical engineer at Waterloo. Although highly technical jobs may be difficult to come by in the first year and may employ more body than mind there are enough jobs for everyone who wants to work (one of us spent one work term unloading box cars, a somewhat unusual work term). In the final work terms most of the students are performing as graduate engineers in their chosen field. For example one of us spent his final work term designing heat exchangers for the chemical industry.

Work reports are written after each work term. They describe a project which was conducted during that term. They seemed to be a chore at the time but looking back they helped develop skills in writing which is often a weak area of engineers. Work term jobs are usually located in Ontario with a few scattered across Canada and the odd jobs in the U.S. and Europe. Major employers are pulp and paper, petrochemical, chemical, food and steel processing companies. In 1974 averaged salaries ranged from \$615/month for first year students to \$670/month for fourth year students.

The social life at Waterloo depends on the individual. Our leisure time was somewhat curtailed by a heavy work load but a host of on-campus activities were available. These ranged from a well developed intramural sports programme to drama, concerts, pubs, dances, movies, etc. Kitchener-Waterloo and the surrounding communities have many fine pubs with the German culture very predominant (typical of this area).

In summary, our years at Waterloo were not the easiest, but were very rewarding. We found that although we were taught to be chemical engineers, the underlying discipline of applying the laws of nature to design may be applied to just about any field. In this way we think we are well prepared for a wide variety of careers." □

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ANALOG SIMULATION OF SAMPLED-DATA CONTROL SYSTEMS

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A GRADUATE COURSE IN SAMPLED-DATA control systems in a chemical engineering curriculum is usually accompanied by a control laboratory in which the student operates a process under computer control and investigates the performance of various control algorithms. If a process computer is not available, some insight into the design and operation of sampled-data control systems can be obtained through simulation on an analog computer. Simulation also has the added advantage that various control strategies, which would be impractical to try with a physical system, can be implemented on the analog computer. The purpose of this article is to illustrate the techniques of simulating sampled-data control systems on a commercial analog computer. This is followed by an example in which these techniques are applied to a practical problem. It is believed that the material presented in this paper will be helpful as an exercise to those who teach or are engaged in work in the area of sampled-data control systems in chemical engineering.

LITERATURE REVIEW

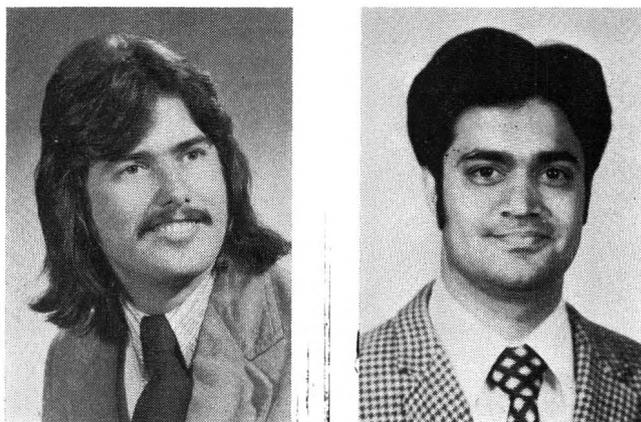
SEVERAL ARTICLES HAVE BEEN published on the general topic of analog simulation of sampled-data control systems. Osburn (1) has described the application of integrators for track-and-hold operation. He has discussed the use of these track and hold amplifiers for stepwise calculations, solution of certain partial differential equations, and for parameter sweep studies.

Kingma (2) has described an equipment called a D(Z) simulator which can be used to simulate

digital controllers without analog-to-digital and digital-to-analog conversion. The simulator uses a modified boxcar generator as the sample-and-hold element. The control pulses for these sample-and-hold elements are generated by one-shot multivibrators. He has applied the procedure to design of a deadbeat controller for an error-sampled unity-feedback system.

Clemence (3) has studied the application of track and hold amplifiers for simulation of sampled-data control systems using digital logic. He has utilized the two complimentary outputs of a flip-flop to drive the track-and-hold amplifiers. His paper includes an example of digital control of a multirate system. In a later article Clemence (4) has described the simulation of a three-mode digital controller by means of track-and-hold amplifiers.

Corripio, et al (5) have studied the analog



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simulation of frequency response of digital control systems. Their paper includes an excellent description of the application of logic components for simulation purposes.

THE ANALOG COMPUTER

AN EAI 580 ANALOG/HYBRID computer was used in this study. The analog portion of this computer contains 38 amplifiers—10 of which can be used as integrators, 50 potentiometers, 8 multipliers, 3 comparators and function relays, 4 track-store units, 4 D/A switches, 8 log diode function generators, and a trunk tray. The logic expansion group on this computer contains 2 counters, 16 AND-gates, 2 general purpose registers (each containing 4 flip-flops), 2 differentiators, and 2 switches. It is assumed that the reader is familiar with analog computer programming so that only the logic elements will be discussed here followed by their application to simulation of sampled-data control problems.

The logic components necessary for simulation of sampled-data control systems on the analog computer are: AND gates, flip-flops, counters, and track/store units. The method of operation of these components is described below.

AND GATES

An AND gate is a basic logic element which has two or more logic inputs. (A logic signal can assume either of the two values: ZERO (zero volts) and ONE (+ 5 volts). The logic ZERO and logic ONE are also referred to as low and high, respectively). The output of an AND gate is high (logic ONE) if, and only if, all the inputs are high. If any of the inputs are low, the output is also low. A simplified schematic of an AND gate is shown in Figure 1(a). The output of the gate is referred to as the true output and the complimentary output (which is the opposite of the true output, e.g., if true output is logic 1, the complimentary output is logic 0) is referred to as the false output. The inputs of all the AND gates on this computer are normally high so that a gate with unpatched inputs has a logic ONE true output.

FLIP-FLOPS

A flip-flop on this computer has three patchable inputs and a true and a false output. See Figure 1(b), and enable patch terminal labeled E can remain unpatched or can be patched to logic ONE source patch terminal to enable the flip-flop. A logic ZERO patched to the E input inhibits the flip-flop. A logic ONE patched to the set (S) input causes the flip-flop to set (i.e. true output is logic ONE) on the next clock pulse. A logic ONE patched to the reset (R) input causes the flip-flop to reset (i.e. the true output is logic ZERO) on the next clock pulse. A logic ONE patched to both S and R inputs causes the

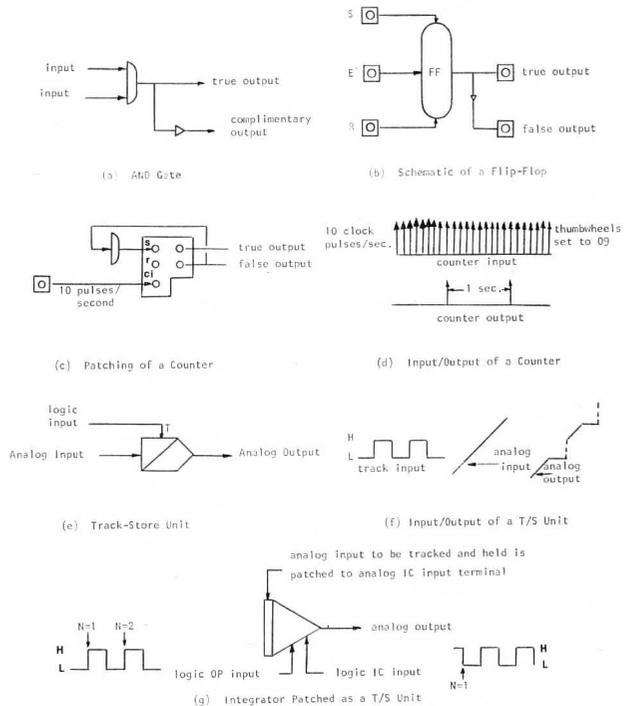


FIGURE 1. Logic Components.

flip-flop to trigger to the opposite logic level on each clock pulse. There are three clock-rate pushbuttons (10^6 , 10^5 , 10^1) which select the clock rate for the logic elements on this computer. If the 10^1 clock rate pushbutton is depressed, the computer provides 10 pulses of logic ONE per second. The clock output is logic ZERO between pulses. Similarly, 10^5 and 10^6 pushbuttons provide one clock pulse every 10 microseconds and every microsecond, respectively.

COUNTERS

A counter has three patchable inputs (S, R, and Ci) and a true and a false output. The schematic of a counter is shown in Figure 1(c). A pair of thumbwheel switches are used to present the counter to any number from 00 to 99. If a clock signal of 10 pulses per second (which is obtained from a 10^1 patch terminal on the logic patch-board) is applied to the Ci input of the counter patched as shown in Figure 1(c), the counter counts down from the number preset by the thumbwheels one count per input pulse. Every time the count reaches 00 the false output of the counter outputs a pulse (i.e. the false output goes high). The false output of the counter is connected back to set (S) patch terminal through a Gate so that the preset number selected by the thumbwheels is loaded into the counter every time the counter reaches 00. An example of the input-output relationship of a counter is shown in Figure 1(d).

TRACK-STORE UNITS

The track-store (T/S) unit has one or more analog inputs, a logic input, and an analog output. A schematic of a track store unit is shown in Figure 1(e). When the

logic input (referred to as Track input and labeled "T" on the T/S unit) is logic ONE, the analog output is minus the analog input. If the T input switches from logic ONE to logic ZERO the unit switches from TRACK mode to the STORE mode. In the STORE mode the output of the T/S unit remains constant and equals the value of the output at the instant of switching. The input/output relation of a T/S unit is illustrated by an example in Figure 1(f). From the previous discussion it is clear that the output of a flip-flop with both of its inputs patched to logic ONE can be used as a logic "T" input for track and store operation.

The computer used in this study is equipped with T/S units. However, if T/S units are not available, an integrator can be patched as shown in Figure 1(g) to perform the track and store operation. When the logic OP signal is high, the integrator will store and when the logic IC signal is high, the integrator will track. Here, the true and false outputs of a flip-flop can be connected to the logic OP and logic IC terminals, respectively, so that the integrator will perform the track and store operation.

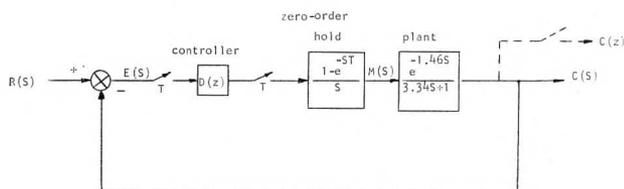


FIGURE 2. Sampled-data Control System.

ANALOG SIMULATION TECHNIQUES

CONSIDER AN ERROR-SAMPLED unity-feedback sampled-data system shown in Figure 2. The objective of the exercise would be to simulate this control system on the analog computer and study the response $C(t)$ of the plant to changes in set point employing a well-known expression for the control algorithm, $D(Z)$. This in turn means that we must represent the control algorithm and the zero-order hold on the analog computer. The plant transfer function is continuous and can be represented on the analog computer by usual means.

Simulation of $D(z)$ Controller:

The pulse transfer function of the controller is

$$D(z) = \frac{M(z)}{S(z)} \quad (1)$$

where M = manipulated variable
 E = error

If we specify the nature of the response, it is possible to obtain an expression for the output of the controller. The time domain expression is usually of the type

$$M^*(t) = a_0 E^*(t) + a_1 E^*(t - T) + \dots - [b_0 M^*(t - T) + b_1 M^*(t - 2T) + \dots] \quad (2)$$

where M^* and E^* represent discrete values of M and E , respectively, a 's and b 's are constants and T is the sampling period.

Thus, from equation (2) it is clear that in order to simulate a digital controller we must be able to perform the sampling, storing, and delaying operations on the analog computer.

The sampling operation is performed by a track-store unit. A square wave of period T is used to drive the T/S unit. As mentioned earlier, clock-rate selection of 10^6 , 10^5 , and 10 pulses per second is possible on this analog computer. The high pulse rates of 10^5 and 10^6 pulses per second are of little use for process control applications. However, the clock-rate of 10 pulses per second can be used for generating a square wave.

If a sampling period of $T = 0.2$ seconds is desired, a square wave can be generated simply by means of a flip-flop whose set (S) and reset (R) inputs are connected to a 10^1 clock-rate patch terminal. The input/output relationships of a flip-flop and the patching in this configuration are shown in Figure 3(a). If a sampling period other than $T = 0.2$ seconds is desired, it will be necessary to use a counter (5). Consider the generation of a square wave with a period T seconds. The patching for this purpose is shown in Figure 3(b). Since we would like the output of the flip-flop to be a square wave of period T , the counter must output two pulses per time period T (i.e. $0.5 T$ seconds between output pulses). It will be demonstrated by an example that if the counter is to output 2 pulses per second, the value to be set on the counter thumbwheels must equal the period between output pulses ($0.5 T$ seconds) divided by the period between the input pulses (0.1 seconds) minus one to account for the pulse that reloads the preset value into the counter i.e. $5 T - 1$. As an example, suppose we like the output of a flip-flop to be a square wave of period $T = 1$ second. Then, the counter output must be 2 pulses per second (or 0.5 seconds per pulse). If we set the counter to $5T - 1 = 4$, the counter will output a pulse every 0.5 seconds. The input/output relationship of the elements of Figure 3

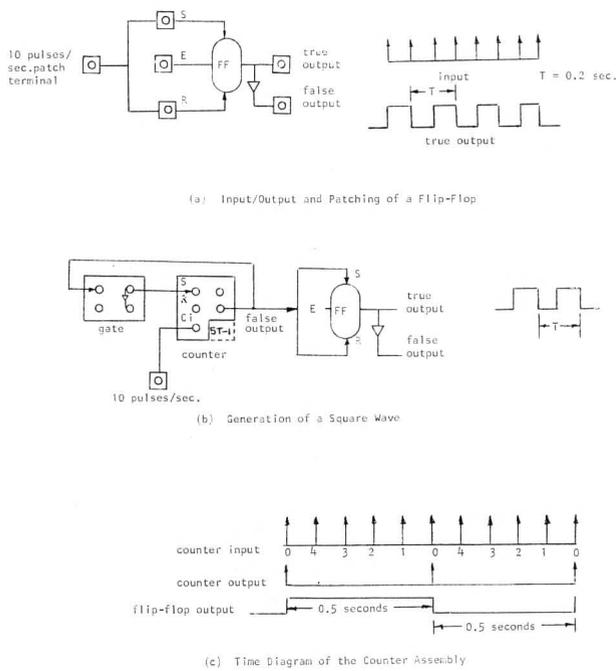


FIGURE 3. Generation of Square Waves.

(b), are shown in Figure 3 (c). These square waves are used to perform the sampling operation. To sample an input, a T/S unit is patched as shown in Figure 4 (a). If a signal is to be delayed by one sampling period, T , two T/S units are used in tandem as shown in Figure 4 (b). As

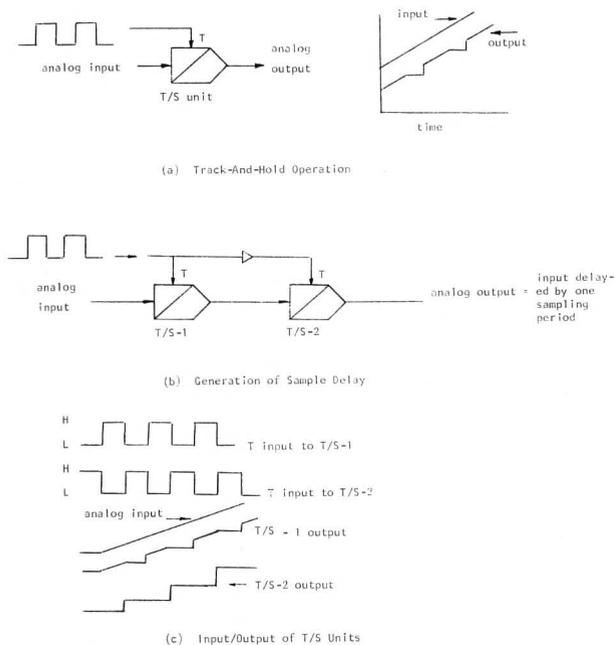


FIGURE 4. Track-and-Hold Operation.

before the true output of the flip-flop generating a square wave is patched to the T input of the first T/S unit. The false output of the same flip-flop is patched to the T input of the second T/S unit. Thus, when the T input of T/S-1 is high the same input of the second T/S unit is low.

Consider the combined operation of two T/S units. When the T input of T/S — 1 switches to high, the analog output of this unit is minus the analog input. During this period the T input of T/S — 2 is low and the output of this unit remains constant. It is equal to the value of the analog input to the T/S — 1 unit at the instant when the T input to T/S — 1 switches to high. When the T input of T/S — 1 switches to low, the output of this unit is held constant at a value it had at the instant of switching but during this period the T input to T/S — 2 is high and the second unit tracks its analog input. The value of the output of T/S — 2 during this period is the value of the analog input to T/S — 1 during the preceding sampling period and a sampling delay of one period T is thus accomplished. An example of the combined operation of two T/S units for a ramp input is shown in Figure 4 (c). It is clear that this procedure can be used for obtaining sampling delay of more than one sampling period by utilizing additional T/S units.

These techniques will now be applied to analog simulation of the digital control system of Figure 2.

EXAMPLE

For the purpose of this illustration, the response of the control system to a change in set point will be obtained on the analog computer using the digital PID algorithm. The response will be compared with that obtained analytically through modified z -transform analysis. The expression for the change in set point which the control system is subjected to is

$$R(t) = 5 (1 - e^{-t/2}) \quad (3)$$

DIGITAL PID CONTROLLER

The digital PID controller is represented in the time domain as

$$m_n = m_{n-1} + k_c (e_n - e_{n-1}) + \frac{T e_n}{\tau_I} + \frac{\tau_D}{\tau} (e_n - 2e_{n-1} + e_{n-2}) \quad (4)$$

where

$$k_c = \text{gain constant}$$

τ_I = integral time constant, sec.
 τ_D = derivative time constant, sec.
 T = sampling period, sec.
 e = error
 m = manipulated variable

The subscript n refers to the value of the variable at the n^{th} sampling instant, $(n-1)$ refers to its value one sampling period before the n^{th} and so on. In this study, $K_b = 2.61$, $\tau_I = 2.512$, $\tau_D = 0.628$, and $T = 0.4$. The process transfer function involves a time lag. In this study a fourth order Pade approximation was used for simulating the transportation lag. The analog computer diagram of the control system with a digital PID controller and a zero-order hold is shown in Figure 5.

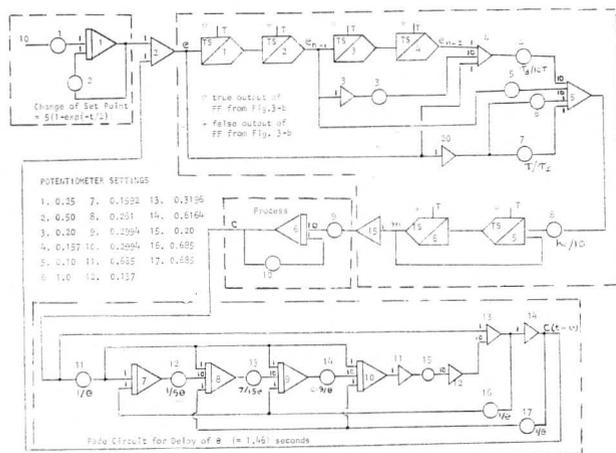


FIGURE 5.

Analog Computer Diagram of the Sampled-Data Control System.

Theoretical Analysis

The response of the control system using the PID control algorithm can be obtained analytically through z -transform analysis. Since a delay is involved, it is convenient to use the modified z -transforms. The parameters of the control algorithm are the same as those used in simulation.

Referring to Figure 2, the block diagram reduction yields

$$\frac{C(z)}{R(z)} = \frac{HG(z) D(z)}{1 + HG(z) D(z)} \quad (5)$$

To obtain $D(z)$, the z -transform of equation (4) is taken to get

$$D(z) = \frac{M(z)}{E(z)} = \frac{7.1233 - 10.8054z^{-1} + 4.0977z^{-2}}{1 - z^{-1}} \quad (6)$$

also

$$HG(z) = Z[H(S) G(S)] = Z \left\{ \frac{1 - e^{-st}}{s} \cdot \frac{e^{-1.46s}}{3.34s+1} \right\} = z^{-3} (1 - z^{-1}) Z \left\{ \frac{e^{-0.26s}}{3.34s+1} \right\} \quad (7)$$

Equation (7) can be simplified via the modified z -transform. Thus,

$$HG(z) = z^{-3} (1 - z^{-1}) Z \left\{ \frac{e^{-0.26s}}{3.34s+1} \right\} = z^{-3} (1 - z^{-1}) Z_m \left\{ \frac{1}{3.34s+1} \right\} \quad (8)$$

From the Tables of modified z -transforms (7), Equation (8) can be evaluated. Thus,

$$HG(z) = z^{-4} \left\{ \frac{0.041 + 0.719z^{-1}}{1 - 0.8871z^{-1}} \right\} \quad (9)$$

Now,

$$R(t) = 5(1 - e^{-t/2})$$

$$R(z) = \frac{0.9063z^{-1}}{(1 - z^{-1})(1 - 0.8187z^{-1})} \quad (10)$$

Equation (5) can now be solved for $C(z)$ which after simplification gives

$$C(z) = \frac{J(z)}{K(z)} \quad (11)$$

where

$$J(z) \equiv 0.264z^{-5} + 0.0627z^{-6} - 0.5518z^{-7} + 0.2670z^{-8}$$

$$K(z) \equiv 1.0 - 3.7058z^{-1} + 5.1379z^{-2} - 3.158z^{-3} + 1.0184z^{-4} - 0.4620z^{-5} - 0.4957z^{-6} + 1.4587z^{-7} - 1.0343z^{-8} + 0.2412z^{-9}$$

Equation (11) can be solved by long division to obtain the values of the response at various sampling instants.

RESULTS AND CONCLUSIONS

THE RESULTS OF ANALOG simulation are shown in Figure 6. Also shown on the figure is the analytical solution.

The slight discrepancies in the two solutions are the result of the approximate nature of the Pade circuit and normal potentiometer round-off errors. However, the difference is slight and can be neglected for the purpose of this work.

It is believed that the material presented here will serve as a useful exercise in analog simulation of sampled-data control systems. With additional

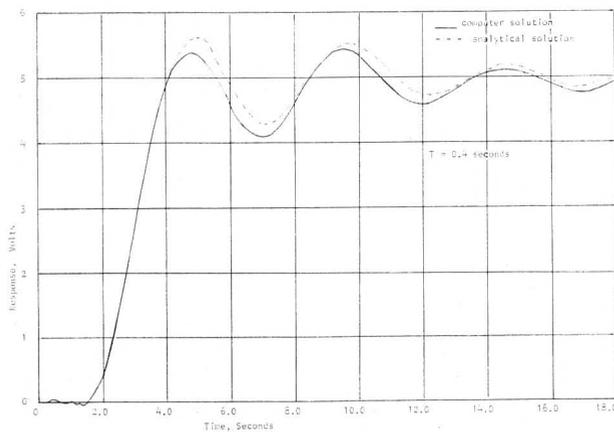


FIGURE 6.
Response of the Sample-Data Control System.

analog and logic components, the general procedure described here can be used for simulating other algorithms such as dead beat algorithm (7) and Dahlin's algorithm (8).

SYNCHRONIZATION

AN ANALOG COMPUTER HAS separate controls for the analog and logic components. For simulation of sampled-data control systems, it is necessary that all the integrators be set in the OPERATE mode at the instant the first clock pulse occurs, after the logic RUN pushbutton is depressed. To achieve this synchronization, an AND gate and a flip-flop are utilized as shown in Figure 7. Figure 7 also shows the timing diagram of the synchronization circuit.

Consider the operation of the circuit. In general assume that the RUN pushbutton is depressed between two clock pulses. The true output of the flip-flop is low until the first clock pulse occurs. Since the SET input of this flip-flop is patched to a logic ONE signal, its true output changes to high at the first clock pulse and remains high after the first clock pulse. At the first

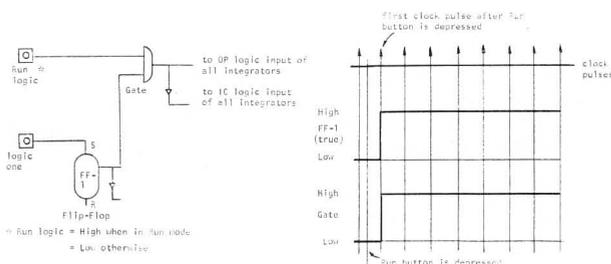


FIGURE 7. Synchronization Diagram.

clock pulse both the inputs of the AND gate are high. Therefore, the true output of the gate goes high at the instant the first clock pulse occurs. Since the true output of the gate is patched to OP logic input of all the integrators, they are set in the OPERATE mode at the instant the first clock pulse occurs. Thus, all the logic and analog components start operating at the same time once the RUN pushbutton is depressed. □

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NOMENCLATURE

- a_0, a_1, \dots = constants of Equation (2).
- b_0, b_1, \dots = constants of Equation (2).
- $C(t)$ = response of controlled variable.
- $D(z)$ = pulse transfer function of the digital controller.
- E, e = error, $R(t) - C(t)$.
- H = zero order hold.
- K_c = proportional gain constant.
- M, m = manipulated variable.
- $R(t)$ = set point
- S = laplace transform variable
- T = sampling period, seconds.
- t = time, seconds
- z = z-transform variable
- Z_m = modified z-transform variable
- Greek
- τ_I = integral time constant.
- τ_D = derivative time constant.
- superscripts
- $*$ = sampled variable

Too Much ChE Research and Teaching Is Dull, Dull, Dull: McGEE

(Continued from page 54.)

SPECIES: CHEMICAL ENGINEERING

WITH THESE INSIGHTS INTO the *genus professorial*, let us now consider more carefully the resulting characteristics of the specific species called chemical engineering.

As a profession we are justly proud of our great breadth, for we are the only applied science profession with in-depth training in chemistry as well as in physics and mathematics. Our background and perspective as scientist-engineers makes for flexibility and adaptability that is the envy of our sister disciplines. A good chemical engineer is rather fearless, ready to attack any problem, and usually with salutary results.

Meanwhile back at the academy, chemical engineering departments nationwide receive about two-thirds of their support for research from one agency—the National Science Foundation. Omitting the recent (and fortunately rapidly growing) RANN program office, the NSF has supported broad basic research wherein any application of research results to our pressing national problems has depended upon only very slightly biased serendipity. Where are the mission oriented agencies in the support of teaching and research programs in chemical engineering? Where are the many offices—ONR, AFOSR, ARO, etc.—of the Department of Defense? Where is NASA? The Atomic Energy Commission? The Office of Coal Research, Health, Education and Welfare? Can it be that the community of chemical engineering professors and their laboratories have relatively little to offer to assist these governmental program officers that are directing huge research and development programs toward identified national goals?

One can get a good idea of what chemical engineering professors and their students are doing by leafing through any issue of the *AICHE Journal* or *Chemical Engineering Science* where the ratio of papers from universities to those from all other sources combined is typically 15 to 1. The following listing presents a few words descriptive of typical papers. In reading these, it is the inference of a tone or a perspective that is intended; the specific subject matter is unimportant; and certainly there is no intent to argue that these papers are worthless.

- An analysis of the motion of simultaneously growing and rising bubbles in a superheated liquid agreed with available data. An analytical solution to the equations of motion was obtained for little bubbles, but the authors had to settle for a numerical solution for the big bubbles.
- A very elegant and neat eigenfunction analysis was presented for the problem of heat transfer between two immiscible fluids flowing down an inclined plane with one fluid on top of the other. Water and mercury were used as a test case.
- Thermodynamic analysis was applied to the calculation of activity coefficients at infinite dilution in ternary liquid mixtures using experimental temperature—composition data. With the assumptions of low pressures and no heat of mixing, the calculational scheme was applied to the ethanol-isopropanol-water system.
- One can measure the viscosity of an oil by noting the time required for a metal cylinder to fall through a vertical column of the oil. An elegant mathematical analysis of the fluid entrance and exit effects around such a falling cylinder has been presented.
- Joule-Thomson coefficient data have been obtained on several ternary mixtures of simple gases and compared with predictions using several popular equations of state. Several earlier proposed ways of combining constants in the equations of state were tested for their relative efficacy.

All of these papers are from chemical engineering departments and describe “research” that is no more than a year or so old. To be sure, these papers were selected to illustrate the thesis of this essay, but the task of discrimination was

The “practice-oriented” curriculum . . . is a false remedy that cannot occur at a respectable university, for teaching without the accompanying scholarship toward the continued evolution of the discipline, is sterile.

very, very easy, for the overwhelming bulk of university papers are well illustrated in tone by the above sampling.

TEACHING AND SCHOLARSHIP ARE RELATED

IF THE ABOVE IS AN indication of the nature of our scholarship, it is also, of course, a good indication of the nature of our teaching as well. If the professor, for whatever reasons, is content to do mundane scholarship, his teaching will also lack this flair of creative vitality. Such a professor may do a good job of presenting the textbook, and perhaps that is adequate for teaching

freshman calculus. But it certainly is not adequate for professional education in chemical engineering where the future of our society is going to depend upon the innovative and inventive character of our graduates. Not how well they know yesterday's textbook, but how well they can invent totally new syntheses of ideas and concepts is the crucial question. And it is exactly here, of course, that the student's association with a creative teacher/scholar is so terribly important. Certainly the greatest teachers of chemical engineering are also themselves the greatest researchers and scholars in chemical engineering. But curiously, the inverse is not true, for great researchers are not necessarily great teachers.

If one may safely correlate the nature of university scholarship as a reflection of the character of the engineering professor's mind and pre-occupations, perhaps it is this same state of mind that primarily determines what other professions and what the lay public thinks of us as a class. Could this have a bearing then on the esteem of engineering in the eyes of many, the view of engineering as the cause of problems rather than a means for their solution, and on the closely related circumstance of our greatly diminished enrollments? Could it bear upon the fact that graduate education in chemical engineering is increasingly left to foreign students as our own young people fail to be attracted by our graduate programs? Surely there must be some relationship.

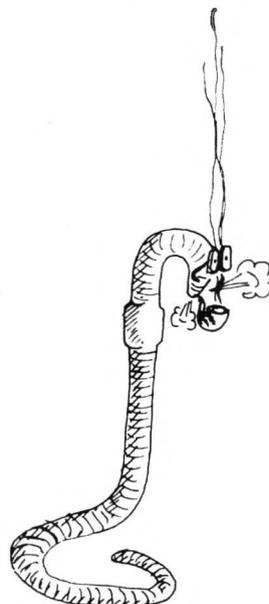
WHAT TO DO?

ONE RESPONSE TO THIS SORT of dull—dull—dull work at our universities is that of a plaintive call for a return to an earlier time,² to a curriculum and to attitudes that are very reminiscent of 30 years ago. According to this argument, we should educate young people who are more able to step into a chemical engineering design situation and immediately perform. We must know more about pipes, pumps, valves, materials of construction, equipment, and economics, with instruction provided by experienced practitioners regarding creative scholarship and and the necessity of publication that were noted earlier.

This "practice-oriented" curriculum and philosophy with its highly practical and immediately utilitarian sort of response is evidently shared by many.³ It is however a false remedy that cannot occur at a respectable university, for teaching without the accompanying scholarship toward

the continued evolution of the discipline is sterile. Even if such a "practice" orientation did develop we would be abandoning all claim to being professionals to adopt a self-imposed exile as technicians. We have too many examples already of technological expertise applied in a manner oblivious to the social and human aspects of the particular situation.

The world needs chemical engineers with the contemplative character of the liberally educated person who will thereby be better able to temper his technological and scientific insights with wise perspectives on the workings of society and on the nature of man. Such attitudes are frequently foreign to the hard-driving chemical engineer in practice as well as to his mentors back at the university. But they are attitudes that are nonetheless essential to the profession. The assertions of many thoughtful and humane individuals are correct, for science and technology are in fact the causal agents of many of our most pressing



Dull?!
Why I published that
in a ChE Journal

human problems. Our responsibility to correct these and to insure more humanely sensitive applications of science cannot be negated by claims of the amorality of science any more than we can expect a diminution of further abuses of science until we as practitioners well integrate our humanistic awareness into our technology.

TRAINING STUDENTS COMES FIRST

A SECOND POPULAR RESPONSE to the dullness of research at the universities is

the claim that the meaning or value of the work is unimportant when compared with the principle thrust or motivation which is after all—the education of students. Our task in academic research, so the argument goes, is one of the teaching the principles of basic and engineering science, of training students, and of acquiring, cataloging, and interpreting a generally useful long-range pool of fundamental knowledge. Working on real problems may even be detrimental to the principle goal of training students, for he would then have to be concerned with economics, societal impact, the press of a time constraint by which deadline his work would have to be completed, proprietary interests, and all the rest. All of this is so confusing and unnecessary when the object really is to teach a student to analyze a technical situation and to reach logical conclusions from his observations.

Unfortunately, in our efforts to delineate and illustrate scientific principles, we often exorcise those very aspects of the problem that make it exciting and meaningful and that illustrate the real world. The claim of such educators that they are, after all, primarily concerned with the training of the student are frightening, for if this be true, they are training the student for a world that does not exist. Though one can argue that it is now, after commencement, the task of industry to sensitize the junior engineer to all of these creative components of engineering, there is nonetheless a great danger, for the student has had instilled into his attitudinal structure in his formative years and by people that he greatly admires, a totally unreal picture of what his profession is all about.

RESEARCH—A DIFFERENT TONE

IT IS UTTERLY UNNECESSARY to take the heart out of university research, as we shall now see.

Consider now a tone or character of research that is today all too uncommon in chemical engineering departments around the country. And so unnecessarily so except for the “professorial syndrome” that we described at the beginning of this essay. All of the following examples are taken, purely as a result of familiarity, from work underway in this Department where we have been making a conscious and prolonged effort to brighten the dull glow. There is certainly no assertion that these are *the* things that chemical engineering educators should be doing, and we

will again suggest that one diminish the specific subject matter in order to infer or sense an attitude or a tone—an altogether different tone from that pictured in the earlier listing.

Renewable natural resources as feed stocks for the production of useful chemicals is a vital concern in these times of shortages of hydrocarbons, concerns for environmental quality, and

Unfortunately, in our efforts to delineate scientific principles, we often exorcise the very aspects of a problem that make it exciting and meaningful and that illustrate the real world . . . the student has had instilled into him a totally unreal picture of what his profession is all about.

the need for energy efficiency. One immediately thinks of plants as such a source, but they produce mostly carbohydrates (starches and sugars), and, in contrast to hydrocarbons, we immediately are concerned with basically reductive rather than oxidative catalysis. Cellulose, the most common organic material on earth, can be enzymatically degraded to its monomer, glucose—a process that is being studied at the Army Natick Labs, Berkeley, VPI&SU, and elsewhere. With an inexpensive source of glucose, one now asks about the chemistry to other products such as hydroxymethylfurfural and from there to amides and other compounds. Sugar cane could be an excellent source of cellulose since it is, from a photosynthetic perspective, one of the most efficient plants known. Glucose can be fermented to ethanol—an important operation when ethylene is scarce and its use to make other products is more profitable. Interestingly, a Japanese firm has recently announced a new polymer called Pollulan which is derived from the fermentation of starch. And certainly tough materials can be made from such renewable resource feedstocks, for the largely protein hide of a rhinoceros can deflect a high-powered rifle bullet fired at close range.

So we have a possible carbohydrate based chemical economy based upon renewable resources with all of the innovative chemical engineering expertise that is implied in such a vision. So what's new in boiling heat transfer? You say you've found a new way to study the effect of liquid wetting of the heat transfer surface?

Consider another example, plants directly

produce a variety of valuable products including foods, flavors, alkaloids and steroids useful as pharmaceuticals. Many of the valuable materials from plants occur in small concentrations or in relatively rare species. The important compounds may also occur only in specific organs of the plant as for example in the seed or in the bark or roots. Conceivably many of these sorts of substances could be produced in pure cell cultures in operations not too unlike a fermentation and at considerable savings in cost. The production of penicillin by deep tank fermentation is a familiar example of the success of such a biological process. The biochemists, of course, first grew the penicillin mold on a shallow nutrient layer on the bottom of an Erlenmeyer flask, so their idea of large scale production was merely to use millions of Erlenmeyers. Dense cell cultures suspended in a nutrient solution and stirred in a closed reactor with sparged in sterilized oxygen was, of course, a chemical engineering development of enormous significance in the modern pharmaceutical industry. Plant cells could be similarly grown, and the production of useful substances of plant origin may then be possible with simple harvesting from the undifferentiated plant cells.

It may be possible to stimulate the production of specific alkaloids, steroids, hormones, and vitamins from appropriate cells. For example, vitamin A or carotene from carrot cells is a legitimate possibility as is morphine from the culture of opium poppy cells. Progesterone, a female hormone and the essential ingredient of the oral contraceptive, is made from a precursor extracted from the Mexican yam. These sweet potato cells then represent an excellent candidate for commercially advantageous tissue culture. Finally, there has been much discussion of possible anti-carcinogens from plants, that is, drugs that would attack cancer in humans. So here again we see exciting potential for developing continuous tissue culture and continuous harvesting as a chemical engineering process. It may even be possible through genetic manipulation and cell fusion to produce interspecies crossings leading to "commercially tailored" plants that could never occur in nature.

So we have plant tissue culture for the continuous production of female hormones, vitamins, and anti-cancer drugs. And so what's new with thermodynamics? You say you have found the Lennard-Jones intermolecular potential function to be superior to the square-well function in cor-

relating Sage and Lacy's p-V-T data on n-butane?

Consider another totally different example. In industrial chemistry, reaction specificity is the name of the game. With a tunable laser, one can do bond-specific photochemistry, and in fact one can be so selective that he can separate isotopes. For example, in a mixture containing HR and DR, using a laser, one can selectively excite DR whereupon it will react with a chemical fixing reagent, F, that is also present to yield a mixture of HR and DF which can now be separated by some routine scheme and the deuterium regenerated. Or

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apply this same idea to the separation of fission essential U^{235} and U^{238} , or to fusion essential Li^6 and Li^7 . The significance of innovations in this area is evident when one recalls that the gaseous diffusion plant at Oak Ridge initially used about one-tenth of the entire electric power production of the United States. The laser technique works, for two Israeli workers have recently described an experimental device using laser excitation, ionization, and electrostatic separation to efficiently produce enriched U^{235} from the natural isotopic mixture in what appears to be a chemical engineering innovation of the first order.⁴

discipline of applying the laws of nature to design may be

In addition to isotope separation, the laser can be used as a pollution monitor by recording the back scatter from a laser pulse in an arrangement that is very reminiscent of radar. It is not necessary to sample or probe the air over the plant. One merely beams in a laser pulse from outside the gate and looks at the backscatter to determine both volatile contaminants and particulates.

So we have lasers for uranium isotope separation, Buck Rogers ray guns, and a sort of probeless pollution monitor. And so what's new in fluid mechanics? You say your latest data reveal a revised exponent on the Reynolds number in your pressure drop correlation equation?

Such a listing can go on and on. With the continuing interest in synthetic hydrocarbons, Fischer-Tropsch chemistry takes on a new attractiveness. Here a mixture of CO and H_2 at a few atmospheres pressure and moderate temperatures is catalytically converted to a mixture of olefins and paraffins in a reaction that could become of singular significance in fuel conversion processes. But it has not attracted much interest in academic circles.

A modicum of library research and talking to people in the field will reveal the shockingly poor

state of our understanding and experience in the chemistry of coal. Conceivably, the fused ring molecules found there could be split, isomerized, and oxidized to, say, terephthalic acid. But coal chemistry is almost unheard of in academe.

The food processing industry involves essentially chemical engineering unit operations, but with materials and under constraints of temperature, sanitation, and the like that are generally foreign to the chemical engineer whose education has been "petrochemical centered." The opportunities there for real impact in canning, freeze drying, quick freezing, evaporation, and waste treatment are enormous. But the universities are mostly silent.

Polymer chemistry is generally at or near the bottom of a priority listing of areas of specialization judged important or most scholarly by most chemistry departments. Excellent polymer science programs have been only recently established at a few universities, most notably at the University of Massachusetts and at Case Western Reserve. But first class programs in polymer engineering with all of the contact with industry that is necessarily entailed are virtually non-existent at universities.

Enough of these examples. The list is far from encyclopedic. It probably does not even contain all of the areas of maximum significance and utility, to which a chemical engineering department might address itself, but one can sense extensive and fascinating possibilities and, more importantly, a tone or an attitude that is very much unlike the current situation at most universities. To interpret this discussion of plant tissue culture, or lasers, or coal chemistry as suggesting that these are *the* things that chemical engineers should be doing is to miss the point completely. Not the merit of these specific ideas, but rather I seek to paint a tone of activity in chemical engineering that is today surprisingly uncommon.

Or finally and on a more homely note, my son took a course in high school called "bachelor cooking." Quite predictably, once you understand the workings of most academic minds, most of the class time was devoted to learning about the various spices and flavors, their sources and how they were produced, the construction of a stove and the temperature distribution in the oven, electric vs gas vs microwave fired ovens, chemical reactions that occur in the cooking processes, and so forth. The fact that one was a great cook and could produce a terrific roast or a great apple pie was quite beside the point. It seemed that one could be a master chef and obtain only an average

or even below average grade in that course. Homely though it may be, this little example is nonetheless a reasonable metaphor of the approach of most academicians to teaching and learning.

CONCLUSIONS

SO, WHAT CAN WE CONCLUDE from all of this? First that chemical engineering is too dull, that this flatness is, in significant measure, a reflection of the dominant preoccupations of the university professors, and, most importantly, that the situation is both unnecessary and fearful. Some of the most crucial problems of our times will be solved, if at all, by the judicious application of chemistry. Chemical engineers are the people best qualified to do it, but we must move away from the conventional wisdom of a total devotion to analysis and the concomitant shunning of synthesis that is now so evident. Rather, our teaching and scholarship must present the essential and complementary values of both. To see only the objective and logical side of everything strips the heart and the zest out of our profession—and out of life as well. Reason and logic can only order and categorize, but we need grand insights and leaps to totally new adaptations of chemical engineering expertise that are characterized by descriptors such as invention, creativity, and synthesis. This will mean a greater emphasis on "process" oriented research rather than on just more "phenomena" research as usual. Our students can be mathematical supermen, and great engineering scientists, but without the ability to invent, they will be failures as engineers.

And in those still very few departments where this devotion to the new and the provocative counters and augments our conventional attention to thermodynamics, kinetics, advanced mathematics, and so on, the natural and certainly not unexpected excitement of it all attracts new adherents like a tumbling snowball. □

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5. Original cartoons furnished courtesy of the chemical engineering department of Virginia Polytechnic Institute and State University, Blacksburg, Va.

Mathematical Methods of Chemical Engineering. Vol. 3. Process Modeling Estimation and Identification.

By J. H. Seinfeld and L. Lapidus.
Prentice-Hall, 545 pages.

Reviewed by R. Aris, University of Minnesota

Any topic in applied mathematics which has attained reasonable maturity will have acquired a considerable primary and secondary literature into which the engineer must dig in his efforts to master its methods. But, if his first steps may seem simple, like those of the descent to Avernus, the task of really penetrating the subject and winning his way back again to the daylight is, as Virgil says, another story—'hoc opus, hic labor est'. Hence the peculiar value of reliable guides to that nether world of mathematical ideas that lies at the foundation of our profession and provides the basis for understanding of chemical processes. Lest it seem ambiguous to commend one's friends as guides to the underworld, I hasten to add that they are no flunkeys of the tourist industry but

members of that select company of erudite guides of which Virgil himself is the best known. For this book will not yield much to the casual reader who thinks he can breeze through it with half his attention, but will be found invaluable by the serious student who wants to understand the modern theory of estimation and identification.

In stressing these, the second and third divisions of the book, I am not overlooking the early discussion of modeling and Laplace transform. A brief introductory chapter leads to a discussion of the types of equation that are of value in modeling chemical processes. The emphasis here is not on illustrating the details of actual derivations, but on the rationale of model building and the types of system that arise and their inter-relations. This is followed by an excellent survey of the Laplace transform which includes both the discrete z-transform and a treatment of the numerical inversion.

There are of course many books available on the Laplace transform and several on modeling, though the treatment here is admirably clear, but what makes this book uniquely valuable is the subsequent discussion of stochastic models, estimation theory and process identification. This covers

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THERMO DIAMOND: Nelson

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the passage of matter. If open systems are considered, the energy flow associated with the flow of matter must be added to each energy definition, *i.e.* $dE = TdS - PdV + \sum \mu_i dn_i$, where μ_i is the chemical potential of species *i* and dn_i is the change in the number of moles of species *i* in the system. Note that *E* is related to extensive measures of the system. We can speak of molar entropy, molar volume, and number of moles in the extensive measures. The enthalpy change has one less extensive change in its definition, replacing the $-PdV$ used in dE with VdP . Similarly, dA has one intensive change in its definition, while dG has two intensive changes, VdP and $-SdT$.

The intensive counterpart of $\sum \mu_i dn_i$ is $-\sum n_i d\mu_i$, and if we draw a second diamond for energy relations in which the intensive term $-\sum n_i d\mu_i$ is used, we replace the pointer terms, dE , dH , dA , dG , with new energy variables $d(TS-PV)$, $d(TS)$, $d(-PV)$, and O (the last not being a definition). Gangi, Lamping, and Eu-

bank elaborate on the relations involving this side of the diamond and have a copyrighted design, called a THERMODORM, to illustrate them. The definition of $d(TS - PV)$ involves one intensive term; those of $d(TS)$ and $d(-PV)$ involve two.

Additional relations may be developed if heat capacities are related to entropy, if electromotive force is related to Gibbs free energy, or if equilibrium constants are related to Gibbs free energy. The reader is encouraged to elaborate these as an exercise. The frequent use of $\Delta H - T\Delta S$ in place of ΔG for processes occurring at constant temperature and pressure may be understood in terms of the diamond. At constant *T* and *P* we have simply $dG = \sum \mu_i dn_i$, which is what dH would be at constant pressure if we subtracted out the TdS term.

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TEMPERATURE PREDICTION: Finger et. al.

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A	=	$A'(M)/K_s$
A'	=	pre-exponential kinetic constant
B	=	E/R_g
c	=	oxygen concentration, moles/liter
		$\frac{AL^2}{cD}$
D	=	$\frac{AH X_o L^2}{k(T_m - T_o)}$
D'	=	$\ln D$
D	=	diffusivity of oxygen
E	=	activation energy
H	=	heat of reaction (per unit of O_2 consumed)
k	=	thermal diffusivity
K_s	=	Michaelis constant
L	=	thickness of decomposing mass
(M)	=	concentration of microorganisms
N_i	=	molar flux of species i
R	=	rate of substrate decomposition
R_g	=	universal gas constant
T	=	temperature, °K
T_m	=	maximum anticipated temperature
T_o	=	minimum anticipated temperature
		$T/(T_m - T_o)$
$T^* _o$	=	value of T^* at $y^* = 0$
μ	=	specific growth rate of microorganisms
μ_{max}	=	maximum specific growth rate of microorganisms
X	=	oxygen concentration, mole fraction
X_o	=	oxygen concentration in the atmosphere
X^*	=	X/X_o
$X^* _o$	=	value of X^* at $y^* = 0$
y	=	distance from center of the decomposing mass
y^*	=	y/L

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ChE Book Review

Continued from page 99.

some areas of comparatively recent development and there is no other reference where a useful introduction can be found in one place. This demands an introduction to probability theory which is provided in chapter 4 where the concept of the random variable and its characterisation is carefully explained. Next comes a discussion of stochastic processes, their description and governing equations. Of particular value here is the explanation of the differences between the calculus of Ito and that of Stratonovich. The sixth chapter on the theory of residence time distributions discovers a habitat where the behavior of both deterministic and stochastic models can be observed.

The remainder of the book is devoted to parameter estimation and process identification, the former being the appropriate task when the structure of the model is fully known, the latter when it is unknown. In both cases there is a natural distinction between linearity and nonlinearity with a simpler set of methods for the linear. In the estimation problem, algebraic, differential equation and stochastic models are discussed, as are frequency domain, moment, gradient and search methods. There follows a valuable chapter on the design of experiments in the light of the estimation problem.

In introducing the subject of the realization of systems for which the structure of the model is unknown the dual concepts of controllability and observability are first explained and some specific algorithms are then developed. The final chapter is on process identification of nonlinear systems, a problem of peculiar difficulty which brings the student near to the frontier of the subject.

For anyone giving a course in methods of process analysis at a graduate level this book will provide a splendid text, while, for the student wanting to study the subject on his own, its organization and clarity make it equally useful. Altogether it is one of the best books in the Prentice-Hall Series in the Physical and Chemical Engineering Sciences.



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