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SUMMER 1970

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Departments

Feature Articles

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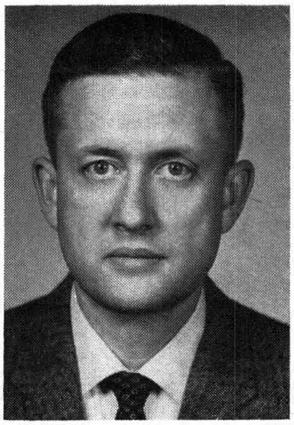
ChE views and opinions

TRANSPORT PHENOMENA: WE HAVE NOT GONE FAR ENOUGH

E. N. LIGHTFOOT
University of Wisconsin
Madison, Wisconsin 53706



Professor Lightfoot was educated at Cornell University, BChE and PhD. In 1953 he joined the Wisconsin department, became active in curriculum revision, and collaborated with Bird and Stewart on the text *Transport Phenomena*. His major research interests are in mass transfer and separation processes and in the appliction of transport phenomena to environmental and biomedical problems.

It is time to take a hard look at what used to be the field of unit operations, and, for most of us at least, it is time to make some fundamental changes. Our present practices overemphasize analysis as opposed to synthesis, and this imbalance seriously distorts both teaching and academic research. The solution to this problem is not to weaken analysis, as some have suggested, but to provide a more powerful and attractive framework for the synthesis aspect of unit operations, which is equipment design. It is also important to eliminate the artificial division between theory and practice, so common in the undergraduate teaching of physical rate processes, but this is a separate problem. Most attempts to combine the introduction of basic principles with examples of practical applications have been based on the elegant but purely descriptive framework of transport phenomena. They have thus aggravated one problem while trying to solve another.

The unit operations are a fundamentally heterogenous collection, and their organization into a single course sequence is an obsolete transition stage in the development of chemical engineering curricula. However the vigorous attempts of the last ten years to replace unit operations by much more systematically organized courses in transport phenomena have not been entirely successful. At Wisconsin, for example, of ten semester credits allotted for physical rate processes only four are devoted to transport phenomena. The remaining six credits are used for rather conservative courses on fluid flow and heat and mass transfer.

The department has consistently rejected suggestions that these ten credits be reorganized to a transport phenomena-based sequence in which introductory of basic theory is immediately followed by discussion of practical applications. I have been disappointed by this attitude in the past, but I now believe that there is a very sound basic objection to this otherwise attractive idea: a well taught course in unit operations was something more than a poorly organized course in transport phenomena. The something extra was an attempt to teach equipment design. The equations of change provide an effective basis for calculating the length of a heat exchanger given the radial dimensions, flow rates, and terminal temperatures. They are not sufficient for determining the configuration or coolant flow rate. They provide no basis for answering such questions as: how would you grind garnets to make sandpaper? They are purely descriptive.

We have overlooked equipment design in part because it was taught unsystematically, but also because of our current emphasis on sophistication and elegance. Synthesis can never be as elegant as analysis, and we can never develop as impressive a framework for equipment design as for transport phenomena. We can, however, improve greatly on our present performance.

We must first recognize that analysis and synthesis are fundamentally dissimilar and should be taught in a course sequence based on the organization of Transport Phenomena (Bird, Stewart, and Lightfoot) or similar texts, and it should proceed directly from fundamental principles to practical examples. The development of such a course sequence is relatively straightforward and should not be further discussed here*. The design aspects must be taught within a much more flexible framework, comparable to that recommended for process design in such references as Strategy of Process Engineering (Rudd and Watson). This framework does not now exist, and a very high priority should be given to its development.

Equipment design must, like process design, be based on a strategy and general principles rather than a set of generally applicable differential eqations. Problem definition is now the precise statement of equipment function. Thus in the sandpaper example above the grinding device must both reduce size and produce sharp-edged particles of compact shape. The remaining stages of the solution will generally require much more detailed physical information than used in conventional treatments of process design, and transport phenomena can be expected to play a key supporting role. The listing of alternative solutions will require an extensive knowledge of physical chemistry. Precedence ordering will now often require ordering of experiments or a mixture of experiments and computations, and it must be recognized that a systematic approach is useful even for very messy problems not amenable to extensive computation.

Development of an undergraduate course in equipment design is now being seriously considered at Wisconsin, and, I would expect, elsewhere. Detailed discussion of such a development is out of place here, but it does seem proper to point out that this type of a course will affect the rest of the curriculum. In addition to a sound background in transport phenomena we must be sure that the student has an adequate practical grasp of applied physical chemistry. I am not sure that this latter requirement is always met. It is also desirable to provide a more extensive historical background in both science and engineering than is now customary, to give perspective and also the faith necessary to successful innovation.

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*This must, however, be done with care. The analogies and contrasts between the three transport processes must be emphasized and a proper balance maintained between theory and application. Simplicity must not be achieved at the price of misrepresentation.

LETTERS

Scenario for the 1970's — January 1, 1980

Sir: This is a report on the decade of the 1970's. Ten years ago, I note that I worried that the population explosion would come to a climax in the 1970's and that its manifestations would be a combination of mass starvation, catastrophic war, uncontrolled pollution, widespread epidemics and exhaustion of essential raw materials. Except for catastrophic war, these things have all happened but not in quite the way I had expected them.

Mass starvation we have certainly had. Back in 1970, we were used to hearing about starvation in India, Pakistan, China and Biafra. During the decade it continued in these countries on an ever increasing scale and to these were added Egypt, the rest of southeast Asia, Brazil, Mexico, Colombia, Venezuela, Peru, the central American countries and all of black Africa. For awhile in the early 1970's, new strains of rice and wheat held out a hope of reducing starvation, but population increases kept pace with the gains in food production. And by 1975 the annual increases in food production, which seemed so promising in the early 1970's, had slowed greatly so that food production remained static after 1975 in most countries, and even declined in some countries, for a variety of reasons.

It is estimated that during the decade, 200 million people starved to death. An accurate count was impossible. There were widespread epidemics in the poor countries, but they were so intermingled with starvation that it was impossible to obtain reliable data on deaths from starvation and from disease. Contrary to many predictions, the "have-not" countries did not blame the "haves" for the epidemics. Starving people apparently do not mind seeing their neighbors die of disease; it reduces the competition for food. Western medical teams won popular support for their unstinting efforts during the epidemics.

Air pollution in the U.S. got no worse in the bad places of 1970—Los Angeles, New York and Chicago—but it spread to many other metropolitan areas. Emission controls on gasoline engines and the widespread use of steam and electric cars has actually made Los Angeles a better place than in 1970. Low sulfur fuels and the development of public transportation improved the situation in New York, Chicago and San Francisco over what it was in 1970. Water pollution on the other hand is considerably worse than in 1970. Lake Erie is a lifeless sump. Lakes Michigan and Ontario are about as bad as Erie was in 1970. The open ocean itself is in poor condition being polluted world-wide and not just from the U.S.A. The Atlantic beaches from Boston to Virginia Beach are unsafe for bathing. A new major cause of death in the U.S. is poisoning from an accumulation of pesticide residues. This affects principally middle aged and older people. Marijuana is now legal and rivals tobacco in sales.

The fears concerning exhaustion of essential raw materials were largely unfounded. We now get 40% of our oil from offshore wells compared to 15% in 1970. In the past decade, we opened up vast deposits of low grade copper and iron. We collect and recycle almost all of the

(Continued on page 116)

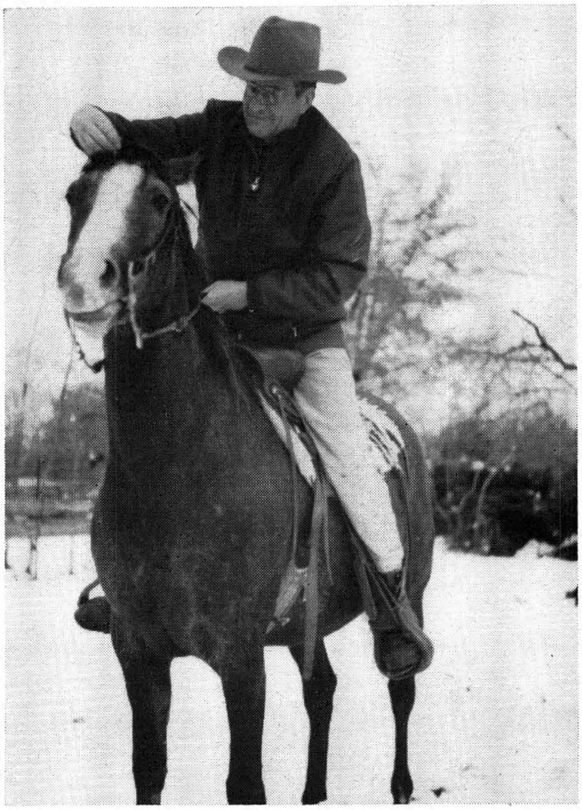
ChE educator

E. B. CHRISTIANSEN -- HIGH ON HORSES AND IDEALS

J. D. SEADER, D. J. WOODSIDE,
AND N. W. RYAN
University of Utah,
Salt Lake City, Utah 84112

HALF A CENTURY AGO, in a rural community known as Richfield, Utah, "industry" consisted of a bit of mining, some processing of agricultural products, and a *lot* of farming. However, there was a boy who looked in growing wonder at the production of cheese from milk, flour from wheat, and at the beginnings of clay and gypsum processing. The desire thereby kindled in him to be a part of this exciting upgrading of materials led him to enter the geological engineering program at the University of Utah in 1928. Nineteen years later, he was to found the chemical engineering department at that institution; but, in the interim, a budding war, some proud Arabs, and a dynamic teacher were to influence profoundly the life of Ernest Bert Christiansen.

After two years at the University of Utah, Chris deserted student life to serve three years as a missionary in Germany, Switzerland, France, and Alsace-Lorraine, where he witnessed the struggles between the Nazis and the Communists, the rise to power of Adolph Hitler, and the burgeoning of German industry. Before returning to the United States, he and a friend purchased a one-cylinder motorcycle and, riding double, commenced a two-month tour that was to lead them through Italy, Greece, Turkey, Syria, Palestine, and Egypt. One evening, happening upon a British police outpost in the hills north of Nazareth, the two young men were regaled with feats of horsemanship by the Arabs manning the post. Though Chris had ridden farm animals throughout his boyhood, he had never before dreamed how beautiful, intelligent, and responsive a horse could be and vowed he would own an Arabian himself someday. As many as five thoroughbred Arabians at a time have since made their home adjacent to the Christiansen residence, looking upon Chris as their owner, trainer, exerciser, and chief vet.



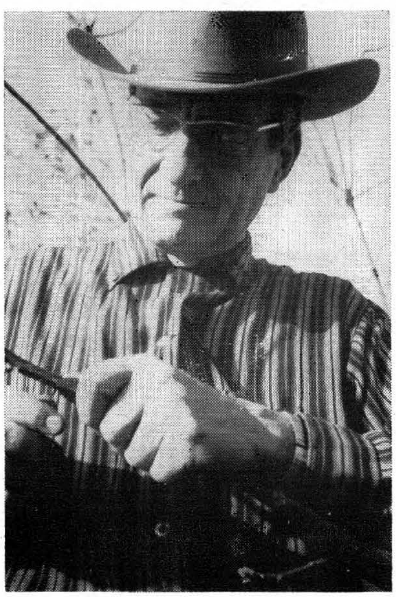
Chris on Sammara, one of his registered Arabian horses.

His broadening experiences in Europe, Africa, and the Middle East had convinced Chris that geological engineering would not satisfy his indefatigable interest in the industrial upgrading of materials. Accordingly, when he returned to the University of Utah in 1934, he changed his major to chemical engineering, then administered by the Department of Chemistry, with all classes taught by one man. By 1937, Chris had completed the requirements for a BS degree, married Susan Mann, and begun to nurture the idea of becoming an educator. As he pursued MS and PhD degrees at the University of Michigan, the idea grew into a firm decision under a dynamic influence: **"I don't believe that anyone could have gone through the graduate program at the University of Michigan and had an experience with G. G. Brown without acquiring an interest in teaching, combined with research and consulting, as he practiced it. . . . Most of us felt we would like to become a G. G. Brown someday."**

Chris believes that a student must be taught the essence of engineering — problem solving . . . "Engineering is the engine of social change; . . . the engineer must be prepared to participate more strongly in the steering as well as the mechanism". . .

However, Chris felt strongly that all chemical-engineering faculty should have industrial experience so that they could present engineering to the students realistically and could outline with first-hand knowledge the requirements for success in industry. Such a person, Chris felt, could speak more competently and, thus, be far more effective than someone who had not had a responsible industrial experience. Therefore, upon completing his PhD in 1941, Christ accepted a position with the du Pont Company's rayon division in Buffalo, New York, at a starting salary of $225 per month! (Chris: "This was somewhat less than offered by some of the other corporations; but the innovations of du Pont in many areas, such as nylon, had caught my fancy." Sue: "I had been working on the Michigan campus for $80 a month; $225 sounded like a fortune!") In a succession of assignments, he developed and designed equipment for producing an electrolytic bleach solution to be used in the spin-bath concentration of viscose rayon; designed the process and equipment for producing a special wartime nylon polymer to be used in "bullet-proof" fuel tanks for aircraft; and, as a member of the du Pont team working on the Manhattan District Project, solved problems relating to the production of plutonium.

Because he had become so engrossed in working out solutions to important industrial problems, Chris had almost set aside his earlier ambition to become a teacher. However, when he was offered the position of professor of chemical engineering at the University of Idaho in 1946, his latent interest was stirred; and he returned to the West. A year later, he became the first (and, thus far, the only) chairman of the Department of Chemical Engineering at the University of Utah, with the charge to develop a full-fledged department to replace the previous one-man operation in Chemistry. He did so with wisdom, his first major decision being to place the department in the College of Engineering rather than in a second college of applied science.



For many years Chris has been trying to develop a late-blooming (to miss Utah's late spring frosts) English walnut.

FACULTY DEVELOPMENT has been wise, also. Of the ten faculty appointees (all holding earned doctorates), only one has left to take another position. Such a stable roster of energetic and productive people is rare. The attributes for which Chris has looked in prospective faculty members are a strong desire to contribute to the growth of young people; a deep commitment to the service of society; potential ability to motivate students to achieve the utmost possible; and, perhaps most important, the intellectual capacity to contribute to the fund of knowledge. Furthermore, he has considered only men who have had industrial experience in addition to their academic preparation. Finally, in recruiting faculty, Chris has avoided hiring only Mormons and local graduates, who were the immediately available applicants. Of the nine he has recruited, only three are of the locally dominant religious faith; and only two hold doctorates from the University of Utah. Chris has thus ensured that the collective experience of the faculty is broad — socially and academically.

Chris has long been concerned with developing in bright young people an interest in chemical engineering, believing that it is necessary to provide a means for junior-high and senior-high students to identify with the profession. This, he feels, can be accomplished by stimulating contact between the students and practicing professional engineers and educators and by developing positive attitudes toward the chemical-engineering profession in high-school teachers of chemistry, physics, and other sciences. Toward these ends, he has encouraged his faculty to participate

Chris sees a bright future for ChE in water and food supplies and environmental pollution . . .

actively in student tours, Career Day presentations, and science-club lectures and has sponsored annual dinners and tours for local high-school science teachers.

The future Chris sees for chemical engineering is bright. In fact, he feels that the chemical engineer is beginning to have his "day" because of his unique potential to solve such problems as the depletion of the world's food and water supplies, as well as the varied and currently alarming aspects of environmental pollution. His intense interest in chemical engineering has influenced all four of his sons. Magazines concerned with science and engineering have always been around the house, readily available for the growing children to read and examine; dinner-table conversations have frequently turned toward creative developments in chemical engineering aimed at solving the problems of modern society; and Chris has often taken his sons to professional meetings so that they could have a first-hand experience with active scientists and engineers. The results of this immersion in a science-oriented atmosphere cannot be disputed — two chemists and two more chemical engineers bear the name Christiansen!

AMONG THE MOST rewarding experiences during his many years as an educator have been Chris' opportunities to review the progress of the many graduates of the University of Utah Chemical Engineering Department. Many have become important contributors to industrial progress, and a number have become educators themselves. Indeed, Chris' influence on chemical engineering in Utah has been felt primarily through the activities of graduates from the department he founded. His influence, both locally and nationally, has also been felt through his outstanding service to the chemical-engineering profession, summarized in the accompanying table.

Chris has developed a philosophy of education that is, perhaps, an outgrowth of his earlier industrial experience. He believes that a student must be taught the *essence* of engineering; namely, problem solving. In spite of many claims to the contrary, Chris knows of no procedure more effective than the use of a variety of experiences in the solution of challenging, relevant problems. He has also been a strong advocate of the need for engineers to take courses in the humanities, stating, **"Engineering is the engine of social change; but, from here on, the engineer must be prepared to participate more strongly in the steering as well as the mechanism."** Easy for Chris to say; throughout his entire professional career, he has been dynamically active in both.

—National AIChE

- Director, 1966-68.
- Chairman: Technical Program, 38th National Meeting; Humanities and Education Area Committee; ten symposia on basic chemical engineering, chemical-engineering education, and humanities at national meetings.
- Member: Nominating, Education and Accreditation, Advanced Seminars, Research, Ethics (ad hoc), Awards Policy (ad hoc), Environmental Project (ad hoc) Committees.
- Council Liaison: Professional Development Committee, Organizing Committee for Agricultural Chemicals Division, Information Systems Committee, five local sections.
- Member-at-large for liaison with Great Salt Lake, Idaho, and Southern Nevada Sections.
- Official AIChE delegate, symposium chairman, and lecturer at III International Congress of Chemical Engineering, Chemical Equipment, Construction, and Automation (CHISA '69), Mariánské Lázne, Czechoslovakia.

—Great Salt Lake Section, AIChE

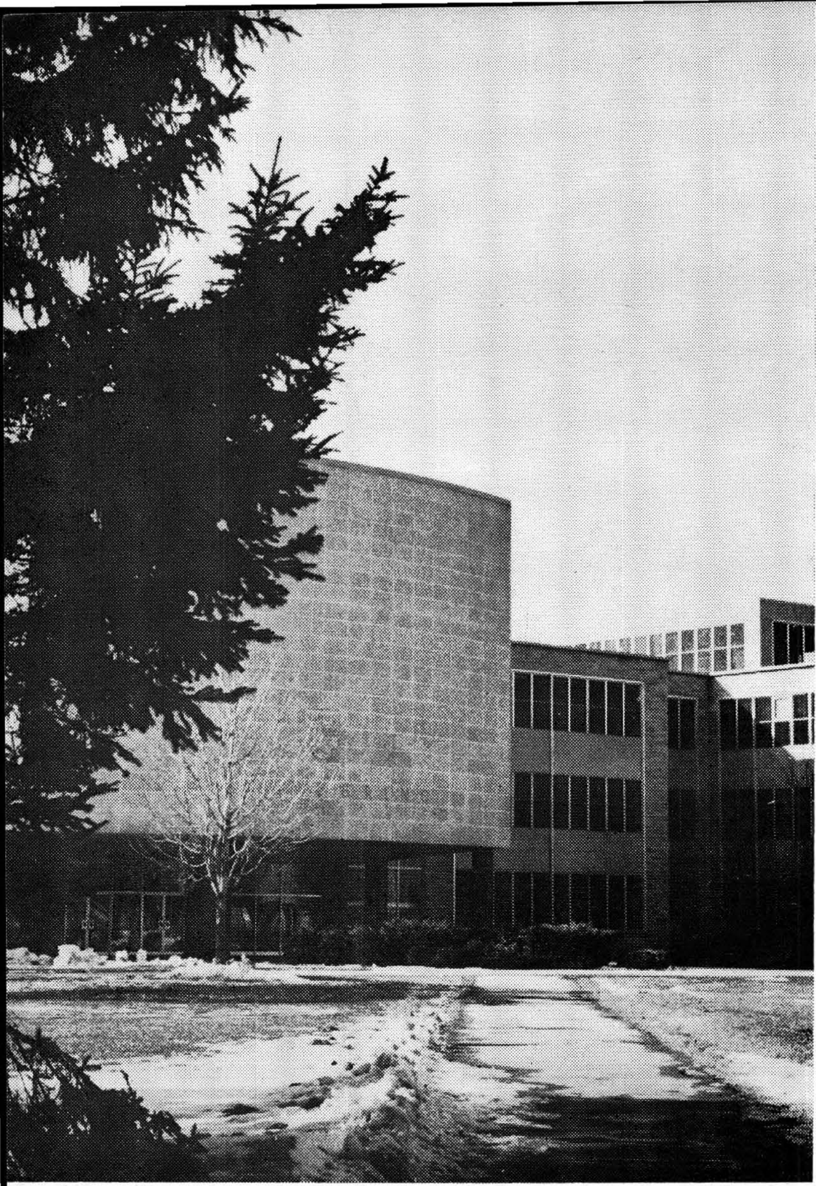
- Chairman: Organizing Committee, 1954; Section, 1956.
- Liaison, 1966 to present.
- Chairman or member of many section committees.

—ASEE

- Chairman: Chemical Engineering Department Heads' Program Committee, 1959 and 1969.
- Member: Nominating, Utah Relations with Industry Committees.

—Other

- Chairman, Local Arrangements Committee, 1971 Winter Meeting of the Society of Rheology.
- Member, University of Utah Subcommittee, XIII International Symposium on Combustion.
- Member, Utah Governor's Committee on Technical Education.
- Member, Professional Standards and Utah Relations with Industry Committees, Utah Engineering Council.
- Chairman or member of many local and regional ACS meetings and symposia.
- Chairman, Salt Lake Chapter, Tau Beta Pi.
- Consultant to the National Science Foundation, the U.S. Office of Education, the Artificial Organs Institute of the University of Utah Medical College, the Heart Test Facility of Bio-Logics, Inc., and several industrial concerns.



ChE department

THINGS ARE HUMMING AT McMASTER

M. H. I. BAIRD
McMaster University
Hamilton, Ontario

The visitor coming to the McMaster Chemical Engineering Department for the first time is usually rather bewildered. The main office on the third floor of the Engineering building is small, crowded and noisy. In all probability he will have to wait there while a free professor can be found. "Prof. A is giving a lecture, Prof. B is at a meeting, Prof. C is on the telephone . . . etc." If he is lucky, our visitor will find a chair to sit on, but often the chairs are piled high with reports and memos. The atmosphere is reminiscent of a newspaper office in a 1940 movie. In short, things hum. The air of this article is to present our philosophy on chemical engineering education, illustrate its application, and perhaps correct our visitor's chaotic first impression!

TO UNDERSTAND OUR PROGRAM and the underlying philosophy of the department, it is necessary to take a brief look at the recent history of chemical engineering in Canada. In 1958, when the department was founded, there were just eight other chemical engineering departments in the country. The emphasis was very much on undergraduate teaching, with 236 BEng graduates being produced in that year, while the graduate student population was only about 75. The undergraduate teaching load for faculty was heavy; twenty contact hours per week were not uncommon. The supervision of graduate students was not considered to be part of the normal teaching load. In the post-Sputnik era of the late '50s and early '60s, both the demand for engineers and the university enrolments soared, and many new chemical engineering schools were created. Today in Canada there are 23 such schools, of which 18 have graduate programs. The 1970 output of BEng graduates is 490, and the graduate student population is 608. This last figure reflects a major change in emphasis since the late fifties.

On the industrial scene, there is and always has been a strong demand for chemical engineers at the bachelor's level. However, since many Canadian companies are subsidiaries of parent companies whose research and design departments are not situated in Canada, the level of industrial research activity is comparatively low. Some Canadian-owned companies have active research departments, but many others do not. The Canadian government has for some years recognized this unbalance providing tax incentives and other assistance for industrial research, and the industrial demand for MEng and PhD chemical engineers has been rising, though more slowly than supply.

CEE features a developing Canadian department that emphasizes design and simulation (as well as fundamentals) and whose unofficial motto is: "The whole must be stronger than the sum of the component parts."

In this department we work hard to maintain strong liaison with Canadian industry with the prime aim of indicating the uses of new and sophisticated problem-solving techniques, and thereby encouraging companies to employ our graduates, both at the BEng and higher levels. The McMaster department has grown steadily since its formation to its present strength of 13 Faculty, a 1970 BEng graduating class of 24, and a graduate student population of 50. The average faculty age is 40 (age range 28-55) and there are seven full, four associate, and two assistant professors. *Our educational goal is to graduate an engineer with a good grounding in fundamentals (versatility), who is technically sophisticated and can use up-to-date techniques of design and analysis (adaptability), who appreciates the importance of new research results and improved knowledge in the field (continuing self-education), who is aware of industrial problems and constraints and who can formulate the right questions, obtain answers and select the most practical solution (relevance), who can communicate with technical and non-technical people (interaction) and who is aware of his professional and social responsibilities (social conscience).*

This broad goal applies equally to the undergraduate and graduate programs: we are constantly examining and re-evaluating the programs so that they may better achieve this goal. The departmental philosophy has evolved over the past twelve years, and include the following tenets. **The emphasis is mainly on technical sophistication and fundamentals, as opposed to teaching "technology" which may change completely in a few years.** On the other hand, we believe in an integration of fundamental science with application. Graduate and undergraduate programs are developed concurrently, and undergraduates are thereby provided with an insight into the vitality of graduate research. Indeed, several of our undergraduate experiments are performed on current graduate research apparatus or may be directed to obtaining peripheral for a research program. All faculty members participate in teaching, research and professional activities—for instance there are no non-researching teachers or non-teaching researchers among us. There are many cooperative projects involving several or all Faculty as well as graduate and undergraduate students. The unofficial motto of the department is "The whole must be stronger than the sum of the component parts." As well as communicating strongly within the department, and thereby develop a philosophy together, we continually interact with other departments at McMaster, industry and the chemical engineering professions. We are acutely aware of the dangers of the "ivory tower" mentality, and for that reason a conscious effort has been made to assemble faculty with industrial experience as well as academic expertise. Innovation in teaching and research are encouraged; indeed experiments on teaching at the graduate and undergraduate level take place every year. Originally, classes were small and there was no tradition to stifle new ideas; although classes are larger now, the early spirit of innovation persists.

THE UNDERGRADUATE PROGRAM starts a year of basic material, common to all engineering departments. In the second year, in addition to further basic courses, there is an introductory chemical engineering course which acts as a bridge between the science already covered and the engineering that is to come. For several years this course has included a cooperative project with local industry (see Fig. 1). Also in the second year, we give one of our most important courses. Information Management. This course runs the gamut of the various means of communication: use of library, computer programming, report

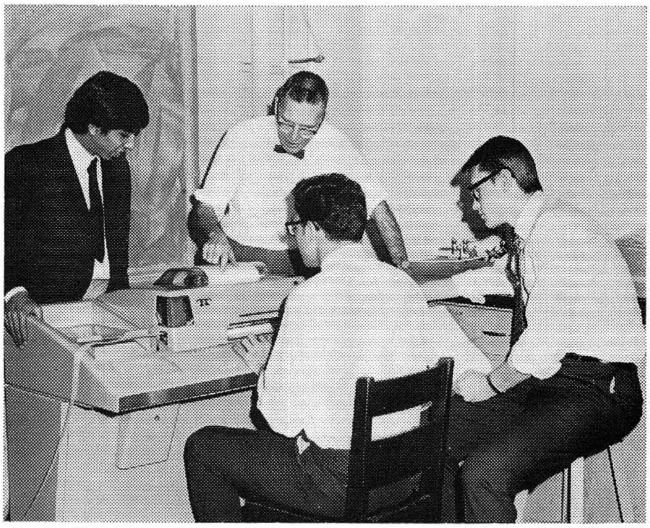


Figure 1. Dr. A. I. Johnson and a group of second-year students discuss a problem in simulating a glycerine evaporator at the Procter and Gamble plant.

writing and oral presentation (via closed circuit TV) are included. There was a marked improvement in our laboratory reports in later years after this course was inaugurated. In our laboratory courses, in third and fourth year, we have broken away from the traditional set experiment to be done in one or two periods. Instead, students are faced with an in-depth project (sometimes the problem is not even defined!) and are given four weeks or more to produce a report. Usually one faculty member is in charge of a given experiment; two or at most three students work on any given experiment. One of our other successful teaching experiments has been the inclusion of a design project near the end of our junior year. Each student is given an objective to be achieved in his experiment and then is guided through the apparatus design by a faculty member and technicians. Several of the best designs have been

We are acutely aware of the dangers of the "ivory tower" mentality, and for that reason a conscious effort has been made to assemble faculty with industrial experience as well as academic expertise.

constructed and used in our teaching laboratory. In these courses, they draw upon the material taught in Information Management and in addition they get a foretaste of industrial project work and academic research.

Nowhere is our philosophy epitomized more than in the undergraduate "simulation project". As implied, the primary aim is to simulate a given chemical process using the CDC 6400 computer available at McMaster. The information so obtained may be used in process improvement, design of new plants, etc. Ten to twelve undergraduates work throughout their final year on each project, with usually three or four coordinated sub-groups studying different aspects of the process. There are weekly meetings of the whole project team which would typically include three or four faculty and six graduate students as well as the undergraduates. These studies concern **real plants** operated by Canadian industry. Our weekly meetings may be attended by representatives of the cooperating companies, and during the project plant visits are arranged as needed. We owe an inestimable debt of gratitude to the companies concerned since the first project in 1965.

These include: Aluminum Company of Canada Ltd.; BP Refinery Canada Ltd.; Canadian

In our laboratory courses, in third and fourth year, we have broken away from the traditional set experiment to be done in one or two periods.

Industries Ltd.; Cyanamid of Canada Ltd.; Polymer Corporation Ltd.; Procter and Gamble Ltd.; Shell Oil Canada Ltd.

The simulations use two computer executive programs, both developed in the department. MACSIM (McMaster Sizer and Simulator) was developed from the Dartmouth College PACER Program. Further details may be found in the book **Chemical Plant Simulation** by Crowe, Hamielec, Hoffman, Johnson, Shannon and Woods, McMaster University, 1969. A hard-cover edition will be published by Prentice-Hall in 1971. Since 1969, we have also begun to use GEMCS (General Engineering and Management Computation System), a system developed here in cooperation with Canadian General Electric Ltd. GEMCS may be run either on the CDC 6400 or on other time sharing computers. The simulation project generates enormous enthusiasm in all who take part, and we are aware of the risk of overemphasis on computation. We therefore urge our students to "compute if necessary, but do not necessarily compute", in other words to look for the consequences of a solution rather than to regard the solution as an end in itself.

This simulation work provides a focus for departmental activities and is the key to our close liaison with industry. It is a means whereby we can apply the expertise of each faculty member to the solution of real problems. It gives us a good excuse to talk to each other about a given problem and thereby increase our breadth of knowledge in chemical engineering. In this way we come to realize each other's strengths. It provides us with an appreciation of industrial problems and perhaps of those areas which require a better understanding; certainly many new research projects have originated through the simulation projects, not only for the simulation group itself but also for the experimentalist as well. There is no doubt that the interaction among faculty on the simulation project has been a major factor in creating an harmonious team of faculty and students.

The above outline has only given the highlights of the undergraduate program; for details the reader is referred to the usual sources. At the present time, the program is being reappraised, with the main objective of providing a number of options in areas such as applied chemistry, applied mathematics (including simulation and control), biochemical engineering, etc. These options would comprise about 15% of the total course units, and they reflect the diversity of interests in the department. Many of the proposed option courses would bring together undergraduates and post-graduate students since undergraduates would take some of the introductory graduate courses which are offered our course-oriented MEng students. Another proposal which is independent of the options program, is for a five-year course in combined chemical engineering and business administration. We are discussing these changes with other departments in the university, with our alumni (via mailed questionnaire) and with our current undergraduate and graduate students. An important input is also provided by the departmental Industrial Advisory Committee which comprises three members from Canadian Industry and one member (currently Dr. S. W. Churchill) from a large U.S. chemical engineering department. We also formed an Undergraduate Curriculum Advisory Committee comprised of three faculty and two student representatives from each of the undergraduate classes and graduate school to undertake studies of various aspects of our undergraduate curriculum. This has proved to be a very successful committee and the interaction with the Industrial Advisory Committee is excellent.

OUR GRADUATE PROGRAM offers two routes to the MEng degree: one is mainly course-oriented, while the other has a relatively light course load and a major thesis requirement. The latter is the usual precursor to entry to the PhD program, although it may be entered directly by a student with a good Master's degree from another school. Prior to presenting the PhD thesis, the student must pass two qualifying exams. These are aimed at ensuring a breadth of knowledge at least as broad as that offered in our bachelor's program, plus the ability to "think on one's feet". The second part of this qualifying examination is related directly to the candidate's research project. Here, the candidate reviews the present status of the research project (literature review), the progress of his program to date and,

One of our other successful teaching experiments has been the inclusion of a design project near the end of our junior year.

Our graduate program offers two routes to the MEng degree.

most important, the direction he has planned for his research. He is then examined in detail on his proposals. An integral part of the program, in addition to course work and research, is the input of practical problems and realism that results from participation in undergraduate projects. Working contact between graduate students and industry is particularly important in the Canadian context, since the opportunities for industrial employment on fundamental research are almost non-existent. A graduating PhD can rarely expect to get a job which relates directly to the expertise obtained in his research program.

The research activity of the department is detailed in our Research Report and is summarized here. The research projects cover a wide spectrum from the most fundamental to the very applied. Our policy is to concentrate on comparatively few research areas, with a back-up of two or more faculty active in each area, rather than having each man "doing his thing" in isolation in one specialized area. The benefits of such interaction far outweigh those of attempting to have an expert in each area. The areas covered are:

- **Applied chemistry:** heterogeneous catalysis, polymerization and reactor design
- **Applied mathematics:** simulation, optimization, computer-aided design
- **Transport phenomena:** heat transfer, fluid mechanics, mass transfer with and without chemical reaction
- **Waste-water treatment**
- **Transport phenomena in iron and steel manufacture**

Several faculty members act as bridges between these five areas, and through associate departmental membership we cooperate with Chemistry, Metallurgy and Mechanical Engineering. Figure 2 shows a typical joint project on solids conveying in a 2 inch pipeline. We have already started interdisciplinary projects with the Health Sciences Centre which is due to open soon, just across the campus, and we look forward to increased activity in this area.

Industrial support for research is less widespread here than in U.S. chemical engineering departments, because of the relatively low level of industrial research activity in Canada. One major industrial project involves the development of a file-oriented, information-handling program, GEMCS, for use on time sharing computers, in

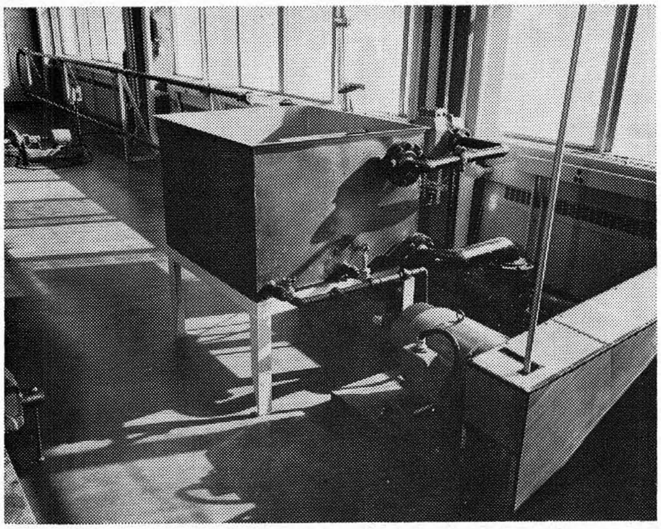


Figure. 2. The Department cooperates with the Mechanical Engineering Department in operating this 80 ft loop for slurry pipeline research.

cooperation with Canadian General Electric Ltd. This program has been used in simulating alternative steel-making processes (Steel Company of Canada Ltd.), and a fat hydrolysis unit (Procter and Gamble Ltd.). A new dynamic simulation program, DYNSYS, has been developed and used in transient and control studies with Polymer Corporation, Dow Chemical Co., and Aluminum Co. of Canada. The Department has just purchased a SUPERNOVA Computer to test in the laboratory, via direct digital control on pilot plant equipment, some of the ideas developed in computer/equipment studies of the dynamic response of this equipment. A number of industrial projects have been carried out through the agency of CARED, the McMaster Centre for Applied Research and Engineering Design (whose Director is a member of the Department!). These include a major study of heavy water separation for Atomic Energy of Canada Ltd. and the simulation of a polymer reactor train.

However, government agencies provide most of our research support. The National Research Council of Canada granted us a total of $205,800 this year. This amount allows for the fact that the university provides overheads, professors' salaries, and partial student support. The Department of Energy, Mines and Resources is granting $100,000 per year (renewable, for up to 5 years) for a major research program on waste water treatment plants.

All the faculty are active in one or more of various professional societies (CIC, CSChE, AIChE, ACS, etc.). The department contains the editorial office of the Canadian Journal of Chemical Engineering, and several of us are examiners for the Association of Professional Engineers of Ontario. We initiated the annual meeting of Ontario Professors of Chemical Engineering, a useful clearing-house of education experience for the eight departments in the province.

In concluding, it is interesting to look ahead to the next 40 years, the working lifetime of our present crop of graduates. What changes will occur in chemical engineering? Will it even exist in 40 years time? Certainly there is a discernible broadening in the scope in which chemical engineers are employed; originally in the 1930s the profession was centered around oil refining, and in recent years the "chemical industry" has been the recognized employment area for chemical engineers. Now in the 1970s we see that in Canada chemical engineers are in demand in such areas as pollution control, mineral processing, and in broad systems studies which may have little formal chemical engineering content. Overlying these new technical needs, there is a growing awareness in the profession that we are accountable for our actions—not only to our employer, but to society and the community. By precept and example, we try to impart this attitude to our students. Hopefully, the teaching and research emphasis in our program will stand our graduates in good stead throughout their careers.

LETTERS (Continued from page 107)

copper, aluminum, nickel and iron that we use. The improvements in technology kept pace with the decline in quality of ores so that the cost of metals and fuels didn't change much during the decade. Garbage and unusable solid wastes are now being hauled considerable distances from metropolitan areas for disposal.

In spite of technological advances the quality of life in the U.S. went down during the decade. The U.S. made little headway during the 1970's on its population problem although some encouraging signs are just beginning to emerge. The ghettos are considerably bigger than they were ten years ago. In spite of massive public housing additions, there were always people waiting to move in every time a ghetto dwelling was vacated. Attempts to interest the poor in birth control were always met by demagogic statements of "governmental genocide aimed at reducing the ghetto dwellers political muscle." In spite of massive expenditures for better schooling in the ghettos, the education remains unable to train people for useful roles in today's society. Crime and lawlessness run rampant in the ghettos. The police do little more than try to contain it at the borders. Drugs, alcohol and marijuana are available at low cost in the ghetto in the hope that it will dull the anger of the residents.

(Continued on page 152)

Beneath this soft and warm exterior, there lies a heart of plastic.

So far, it's only a valve. Eight-year-old Janet Hernandez has one.

It may not be long before a whole working heart will be made out of plastic.

Men in plastics research at Union Carbide are working on the almost impossible job of designing plastics compatible with the body.

Their most crucial job is making an ultra-thin polypropylene fabric for lining the inside of the heart. A fabric coated with parylene that will allow human tissue to grow into and around it to keep blood from clotting.

A plastic heart isn't the only part of the body we're working on. Maybe someday there will be a little plastic in all of us.

Right now, we've got you surrounded by our plastics. We were in plastics before most people knew the word. We make more plastics than anyone else. We haven't scratched the surface yet.

Why is a great big company like Union Carbide so concerned about a little bit of plastic for the body?

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Beneath our corporate exterior, there beats a heart.

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USE OF VISUAL INTERACTIVE DISPLAY IN PROCESS DESIGN

T. JUUL-DAM, J. D. LAWSON,
L. A. MADDOX, and H. F. RASE
The University of Texas at Austin 78712

Both ChE students in process design classes and practicing process engineers have long been plagued by the necessity of doing many tedious and methodical calculations before reaching the more interesting and creative aspects of design. The advent of high speed computers generated great hope that both the professional engineer and the student would be freed from tedium and would be able to concentrate on the heart of any engineering problem — the exercise of engineering judgment and innovation. Unfortunately, in practice this hope has not been totally realized. Even if one assumes that the programming and "debugging" are done by others, several crucial issues remain which detract from the real engineering meat of the problem.

- Although the usual process design calculations can be done in seconds, the actual time measured from the time of submitting input data to the receipt of the printed results can be many hours. The reason for this is simply that large computers in any organization are used by many people. Time sharing makes this use an orderly, efficient process, but some kind of priority system must be established which often relegates many problems to longer waiting periods. This is especially true in a university where involved research calculations may take a large portion of computer time.
- The results when obtained consist of the familiar long printout of masses of numbers which is essentially unintelligible until one produces some sort of graph that enables analysis of trends. This further delay is particularly annoying during the earlier stages of contact with the problem when the student or designer has little feel for the way variables interact to effect outcomes, and is anxious to overcome this deficiency. Chemical reactor design, because of the associated nonlinear systems of differential equations is an excellent example of a problem requiring detailed calculations merely to acquire a feel for the problem.
- In the early stages of a problem the designer must decide how the stated purposes are to be accomplished. It is during this aspect of the problem that he exercises his creative abilities and makes some of the most critical decisions of the project. Although the creative act remains essentially a mystery to psychologists and others who have attempted to study it, it seems rather clear that it usually occurs most successfully when one is totally immersed in the problem and is obtaining the results of tentative ideas in a rather rapid and orderly fashion. This climate is not provided by the usual mode of interacting with the digital computer as described above. Relatively long waiting periods for receiving results together with the presentation of these results in long printed format cause the mind to wander from the problem and require that one renew his interests and reestablish his previous viewpoints each time a series of results is received. Of course, one can submit a number of different designs at one time. In any real situation, however, one is apt to submit a number of cases which are trivial and do not necessarily converge to the desired result. This can be a very common and natural consequence of an inadequate intuition about the variables during the early stages of attack on a problem.

An obvious and much more desirable beginning on a design problem would involve toying with the variables and immediately observing the results in graphical form. An interactive visual display is ideally suited for this purpose. We have recently adapted such a unit for use by members of the senior class in process design, and the results have been most gratifying. Each student in two separate twenty minute periods was able to master rather complete understanding of the impact of the several variables on the problem and developed a feel for the issues which enabled him to make major engineering decisions. This encounter with the visual display of profiles of variables was then followed by an opportunity to accomplish study of a well planned series of cases using the more common procedure of submitting and receiving design cases from the digital computer in printout form. The second phase of work now, however, was intelligently planned and executed for the purpose of obtaining precise quantitative results for a rather well-defined system, major decisions on operating conditions having been fairly well decided by use of the visual display.

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The proof of the efficacy of this procedure can best be realized by observing the effect on students. The encounter with the visual display is essentially a teaching encounter in which the student teaches himself about the problem. It is rather inspiring and somewhat surprising to see how rapidly a student becomes very knowledgable about the important issues. Students seem to be overflowing with ideas at this stage and become most anxious to proceed with testing these ideas further. Even the average and below average students are stimulated and their abilities extended to the maximum. The use of visual interactive displays has received a great deal of attention in mechanical design, and it also now seems to possess equally exciting potential in process design.

In order to provide interested readers with some insight into the issues involved in planning and executing the use of visual interactive displays, we will present some of the details of a reactor design problem and the issues involved in selecting the variables for display.

THE DESIGN PROBLEM

The design problem was stated simply: Design a catalytic reforming unit for producing 20,000 BPSD of 95 research octane number reformate.

Hydrodesulfurized Feedstock Analysis

The feedstock has API gravity of 51.9° and volumetric composition of 43.4% paraffins, 40.0% naphthenes, and 16.4% aromatics. Data for the ASTM distillation are: IBP—240°F; 10%—262°F; 20%—272°F; 30%—279°F; 40%—284°F; 50%—292°F; 60%—302°F; 70%—311°F; 80%—322°F; 90%—335°F; 95%—346°F; and EP—369°F.

Catalyst

The catalyst is Sinclair-Baker RD 150 (0.6% Pt-on-alumina), 1/16" extrudate and has bulk density of 0.78 gm/cc; surface area of 471 m^2/gm; and pore volume of 0.42 cc/gm.

Catalyst characteristics: Poisoned by sulfur, arsenic, and nitrogen compounds. Coking occurs on the catalyst and deactivates it gradually. Regeneration by burning with air partially restores the activity. Catalyst life declines with increasing operating temperature and decreasing pressure.

Idealized Rate Equations[7]

A number of references on the process were supplied[1-10] including kinetic data.[7] The following equations apply:

Each of the three hydrocarbon classes is represented by a single compound having the average properties of that class.

1. Naphthene $\rightleftarrows$ aromatic + $3H_2$; $\Delta H_1 = 30{,}500 \dfrac{\text{Btu}}{\text{mole } H_2 \text{ liberated}}$

$$-r_1 = k_{p1}\left(P_N - \frac{P_A P_{H2}^3}{K_{p1}}\right)$$

$$k_{p1} = e^{\left(23.21 - \frac{34{,}750}{T}\right)},\ \frac{\text{lb-moles naphthene}}{(\text{hr})(\text{lb cat})(\text{atm})}$$

$$K_{p1} = e^{\left(46.15 - \frac{46{,}045}{T}\right)},\ \text{atm}^3$$

2. Naphthene + H_2 $\rightleftarrows$ Paraffin; $\Delta H_2 = -19{,}000 \dfrac{\text{Btu}}{\text{mole } H_2 \text{ consumed}}$

$$-r_2 = k_{p2}\left(P_N P_{H_2} - \frac{P_P}{K_{p2}}\right)$$

$$k_{p2} = e^{\left(35.98 - \frac{59{,}600}{T}\right)},\ \frac{\text{lb-moles naphthene}}{(\text{hr})(\text{lb cat})(\text{atm})^2}$$

$$K_{p2} = e^{\left(\frac{8{,}000}{T} - 7.12\right)},\ \text{atm}^{-1}$$

3. Paraffin + H_2 $\rightarrow$ Hydrocracked Products; $\Delta H_3 = -24{,}300 \dfrac{\text{Btu}}{\text{mole } H_2 \text{ consumed}}$

Stoichiometry: $C_nH_{2n+2} + \frac{n-3}{3} H_2 \rightarrow \frac{n}{15}[c_1 + c_2 + c_3 + c_4 + c_5]$

$$-r_3 = k_{p3}\frac{P_P}{P_T} = k_{p3}Y_P$$

$$k_{p3} = e^{\left(47.97 - \frac{62{,}300}{T}\right)},\ \frac{\text{lb-moles paraffin}}{(\text{hr})(\text{lb cat})}$$

4. Naphthenes + H_2 $\rightarrow$ Hydrocracked Products; $\Delta H_4 = -22{,}300 \dfrac{\text{Btu}}{\text{mole of } H_2 \text{ consumed}}$

Stoichiometry: $C_nH_{2n} + \frac{n}{3} H_2 \rightarrow \frac{n}{15}[c_1 + c_2 + c_3 + c_4 + c_5]$

$$-r_4 = k_{p4}\frac{P_N}{P_T} = k_{p4}Y_N$$

k_{p4} = same as k_{p3}

. . . the creative act remains a mystery, but it seems clear that it occurs most successfully when one is totally immersed in the problem and is obtaining the results of ideas in a rapid and orderly fashion . . . the visual display expedites the creative process . . .

The value of n is obtained from the molecular weight of the feed and the mole fractions of the feed component types as described by Smith.[7]

Balance Equations in Difference Form

Material:

$$(-r_1)\frac{\Delta W}{F_T} = \Delta x_1 \qquad (5A)$$

$$(-r_2)\frac{\Delta W}{F_T} = \Delta x_2 \qquad (5B)$$

$$(-r_3)\frac{\Delta W}{F_T} = \Delta x_3 \qquad (5C)$$

$$(-r_4)\frac{\Delta W}{F_T} = \Delta x_4 \qquad (5D)$$

Heat:

$$\frac{\Delta W}{F_T}\left[(-r_1)(-\Delta H_1)(3) + (-r_2)(-\Delta H_2) + (-r_3)(-\Delta H_3)\frac{n-3}{3} + (-r_4)(-\Delta H_4)\left(\frac{n}{3}\right)\right] = \sum_{i=1}^{9} N_i\, C_{p_i}\, \Delta T \qquad (6)$$

The reason for use of adiabatic reactors in all industrial installations of this process was first established in discussions with the students. By proper choice of initial condition Reaction 1 is made to proceed to the right and Reaction 2 to the left. These events are both highly endothermic and demand staging and intermediate heating.

The balance equations were programmed for the iterative calculations necessitated by the coupling of Equation 5A-D and 6. Variables selected for appearance on the visual display are limited by the capacity of the oscilloscope to produce a readable graph. Thus, items were chosen that would contribute most to the students grasp of the problem and understanding of the sensitivity of the more important rates to changes in variables. The cumulative volume per cent aromatics in the C_5+ reformate, which is correlated with octane number, and the rate profiles of aromatics production and paraffin hydrocracking were selected for visual display as a function of W/F (reciprocal space velocity). These rates have an overriding effect on octane number of the finished product. Volume per cent aromatics is not only affected by the amount of aromatics formed but also by the extent of hydrocracking, which acts to decrease the volume of C_5+ paraffins in the product and thus increase the net volume per cent aromatics.

At the end of each trial design the designer also needs to know the yield, which is most desirably expressed for a product sold by volume, as volume of C_5+ product divided by volume of feed.

Use of the Visual Interactive Display

These variables were plotted as shown in Figures 1 - 3. All are graphical except the yield figure which appears as a number at the end of each trial on the lower right hand corner of the screen. The user selected the number of reactors, the inlet temperature, average pressure and space velocity for each reactor by punching the keyboard as shown in Figures 4 and 5. This simple keyboard could be mastered by anyone, even a person not familiar with the problem. Thus, it was possible for a student to use the keyboard freely and let his ideas develop without inhibition.

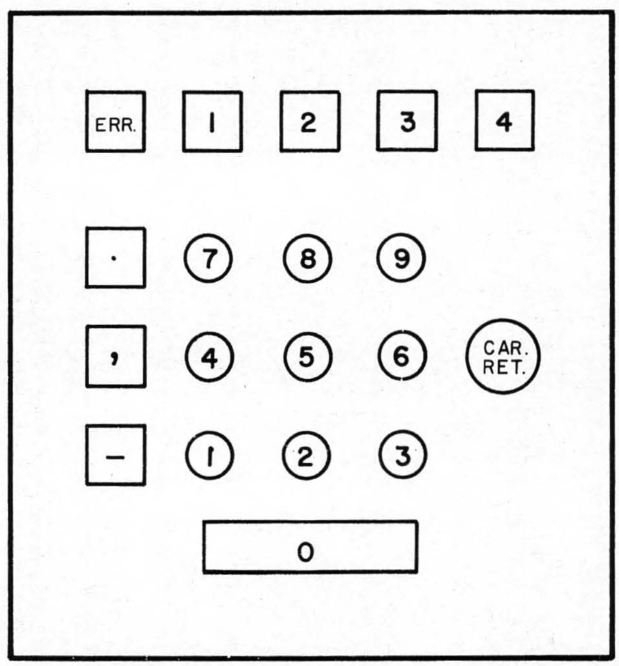

Fig. 4. Keyboard. The top row of keys is used to select the class of variable, e.g., temperature, pressure, W/F, and numbers of reactors. The particular reactor of interest and the magnitude of each variable is specified using the lower array of keys.

Typical Trial Run on the Display

After initial random trials or prior study of literature on existing reformer plants the stu-

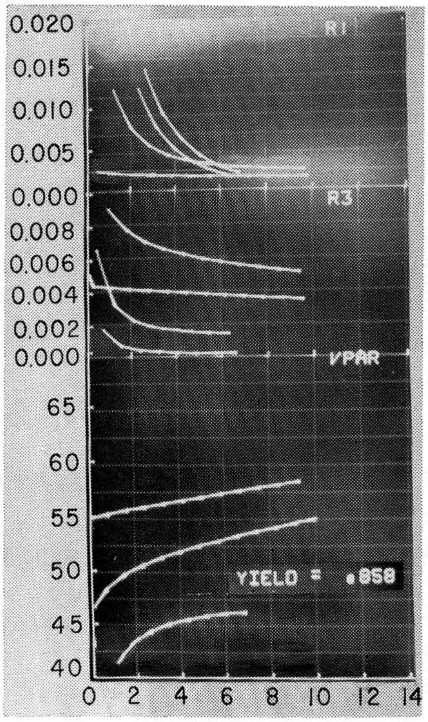

Fig. 1. View of display for Trial 1.

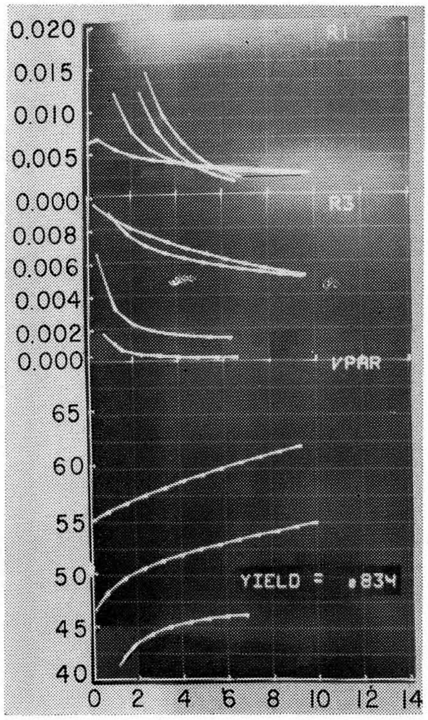

Fig. 2. View of display for Trial 2.

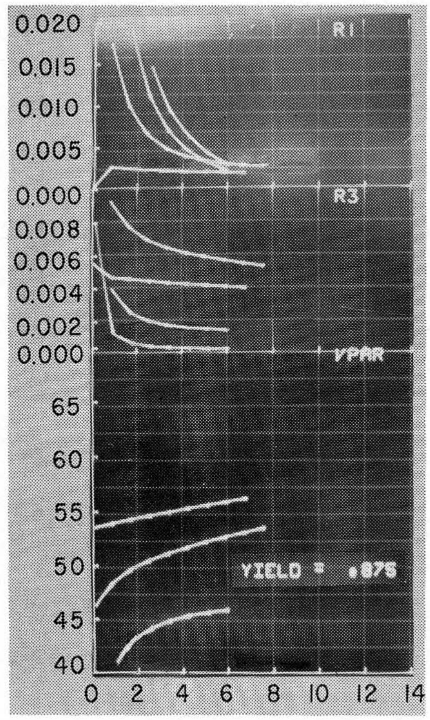

Fig. 3. View of display for Trial 3.

X axis division 2. Y axis division R1 = 0.005, R3 = 0.002, VPAR = 0.05 beginning at 0.4. R1 and R3 are rates of reactions 1 and 3 respectively. VPAR is volume per cent aromatics.

dent decides that a reasonable set of input values would be as follows:

Trial 1: (Fig. 1) No. of Reactors 4

T	950	950	950	950
P	475	450	425	400
W/F	7	7	10	10

From the display the student realizes that a volume per cent aromatics (VPAR) of 62.9 at outlet of last reactor is above his product quality specification (57% required) and that his yield is not particularly good. The student reasons that possibly eliminating the re-heating between the 3rd and 4th reactor would cause less hydrocracking of paraffins which would lower his product quality to a more acceptable value and also simplify the design of the reformer. From previous trials the student knows to expect a temperature drop of approximately 25°F in the third reactor. The student then changes the inlet temperature of the 4th reactor to give:

Trial 2: (Fig. 2) No. of Reactors 4

T	950	950	950	925
P	475	450	425	400
W/F	7	7	10	10

The student sees that the results of Trial 2 are a VPAR of 58.25 which is near the range of product quality desired. He also is pleased to see that the yield has increased to 85.8%.

Upon examining the rate of conversion of naphthenes to aromatics (the top-plot-R1) he sees that R1 has become quite low near the end of 1st and 2nd reactor. He, therefore, reasons that the 1st and 2nd reactor should be made smaller. Also, since the product quality could still be lower and be acceptable, he decides that he will need less cracking of paraffins and can therefore shorten both the 3rd and 4th reactors. These inferences lead to

Trial 3. (Fig. 3) No. of Reactors 4

T	950	950	950	925
P	475	450	425	400
W/F	6	6	7.5	7.5

The student notes that R1 has not fallen to as low a value as in Trial 2. He sees that his product quality has dropped to a VPAR of 57.0% which is quite acceptable to him and he is also rewarded with a much higher yields of 87.5%. He also recognizes that Reactors 3 and 4 can be

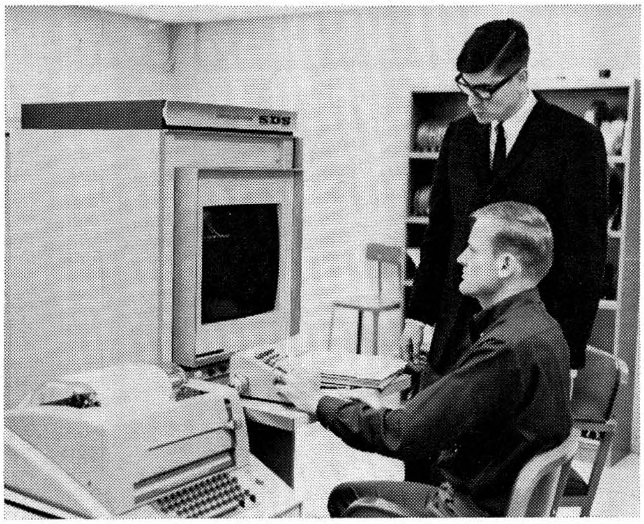

Fig. 5. Student operating display under observation of teaching assistant.

combined into a single reactor if vessel economics so indicate.

Description of Computer Equipment and Program

Equations 1 through 6 were programmed to calculate the rates of reaction, temperature profiles, and material balances through the length of fixed bed catalytic reactors. An iterative technique was used to balance the heats of reaction and reaction rates for small increments of catalyst bed based on an arithmetic average temperature for that increment. Once a balance was reached for one increment of catalyst bed, the outlet temperature and component flow rates were used as inlet values to the next increment of catalyst bed. The computation continued until the prespecified amount of catalyst had been used. The program allowed the student to specify the number of reactors and the inlet temperature, average pressure, and space velocity of each reactor.

The program was modified to run on a Scientific Data Systems Model 930 computer coupled to a Model 9185 Scope Display having vector and character generators. The unit had 32,000 words of memory. The program was operated under the special University of Texas Tape Monarch system containing a custom multigraphics package for the scope.

CONCLUSION

It can be seen from the description of a series of trials by a student that the student rapidly acquires knowledge about the process. He is motivated by the ease and rapidity to try new ideas of all types. We have found that great enthusiasm for the problem is generated by this encounter with the visual display, and many of the students have indicated genuine originality.

ACKNOWLEDGMENT

We are grateful for assistance and advice from Dr. C. L. Coates, Dr. J. K. Aggarwal and Messers Richard Wackerbarth, John Bradley and David Hogan, all of the Electrical Engineering Department of the University of Texas.

NOMENCLATURE

C_p = heat capacity
F_T = total fresh feed, lb-moles/hr
ΔH = heat of reaction, see text
k_p = velocity constant based on partial pressure, see text
K_p = equilibrium constant in pressure units, see text
n = number of carbon atoms
P = pressure, atm
r = reaction rate, $\frac{\text{lb-moles converted}}{\text{lb cat-hr}}$
W = weight of catalyst, conversion
x = conversion, $\frac{\text{moles converted}}{\text{mole total fresh feed}}$
Y = mole fraction

Subscripts:

A = aromatic
H_2 = hydrogen
i = any component in reaction mixture
N = naphtha
P = paraffin
T = total

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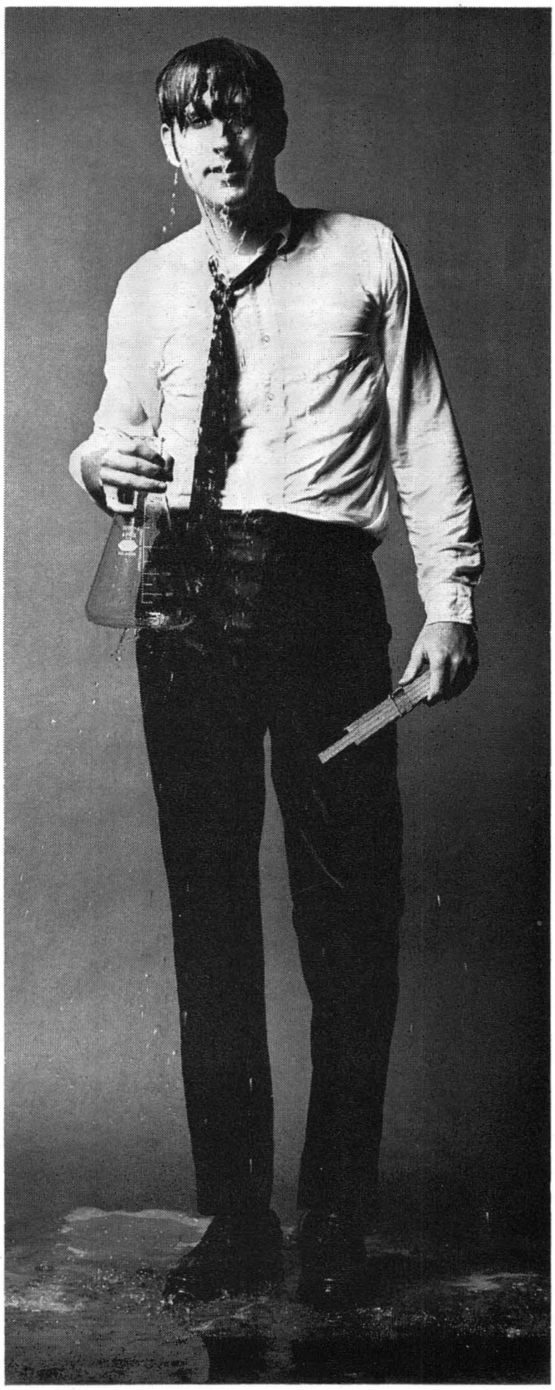

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CASE PROBLEMS IN CHEMICAL PROCESS DESIGN AND ENGINEERING

ChE classroom

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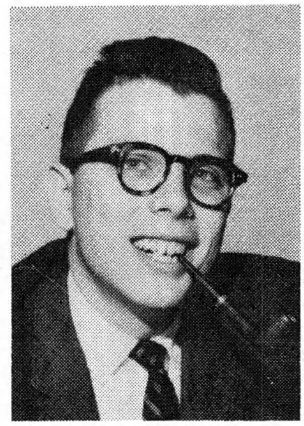

C. Judson King is Professor of Chemical Engineering at the University of California, Berkeley. His principal teaching and research activities lie in the fields of process synthesis and development, separation processes, food dehydration and mass transfer. He is the author of a new textbook, "Separation Processes," to be published by McGraw-Hill in late 1970. He holds the BE from Yale University and the SM and ScD from MIT. Since 1967 he has been Vice-Chairman of the Berkeley chemical engineering department.

A major challenge to chemical engineering education is the need to develop students' abilities in the *art* of engineering. Present-day curricula concentrate upon analysis and the understanding of physical and chemical phenomena. A chemical engineer must necessarily have a strong background in these areas; yet engineering is inherently an active, problem-solving function, for which analysis and scientific understanding are only the tools. We devote considerable time to developing the tools, but usually spend much too little time developing skills in the integrated use of these tools for the synthesis of new processes and for coping with other real, complex and loosely-structured problem siutations.

Universities can and should provide the training to bring out talents of application and problem-solving in students. Leaving this job to industrial experience runs the risk of these talents never being developed at all, and results in specific methods and customs being passed on from one generation of engineers to the next without the young engineer being encouraged to question and to bring in a fresh approach.

BERKELEY GRADUATE DESIGN PROGRAM

These conclusions have led this department to stress chemical process design and engineering as an important portion of the available graduate program. This portion of the graduate program is under the principal direction of four full-time faculty members: Professors Alan S. Foss, Edward A. Grens II, C. Judson King, and Scott Lynn. Courses are available in Process Simulation in Chemical Process Design, Chemical Process Synthesis, Design and Engineering of Integrated Chemical Process Systems, and related areas. The first three of these courses emphasize not only techniques which are available, but also the application of these techniques in specific chemical processing situations. The fourth course is built around a sequence of short case problems of the sort described below, and the development of these problems is an important aspect of the program. MS and PhD degree requirements are equivalent to the rest of the graduate program, and a thesis is required for each degree. Theses in the process design and engineering program represent original and potentially publishable work in the development and improvement of design concepts and techniques, or of specific processes. Thesis research and the creation of case problem material for use in class are often closely connected. Ties with industry are maintained through short-term (typically one quarter) visitors to the program and through the previous industrial experience of the faculty involved. The program is currently supported by a short-term initiation grant from the Division of Graduate Education in Science of the National Science Foundation.

CASE PROBLEMS

The case problems generated and used in the program are for the most part short enough so that they can be handled through class discussion in a relatively few class periods, with intervening homework assignments. They are not the sort of course-long problem typically taken up in a senior-year design course or in the AIChE Student Contest Problem; instead they are shorter and more qualitative. They are intended to increase the student's abilities in synthesis, in basic process understanding and in coping with open-ended engineering problems. The student must solve the problem himself; he does not read a history of someone else's solution. The problems are similar to those presented by Thomas K. Sherwood in his book, *A Course in Process Design,* and to those presented in *Chemical Engineering Case Problems* published by the *AIChE* Education Projects Committee in 1967.

At Berkeley these case problems are used as the entire subject matter for the aforementioned graduate course and also for a senior-year elective undergraduate course which follows the required senior design course. It is also possible to use one or more of the problems as a portion of a lecture course, for example as a means of tying together and showing application for subject matter at the end of a course.

HOW TO OBTAIN PROBLEMS

Through the grant from the National Science Foundation, these Case Problems are available to faculty of other universities for the cost of Xerox duplication. Each problem consists of a short descriptive introduction with references, a suggested Problem Statement for issuance to the students, and an extensive discussion or "Solution" of the problem for faculty use. This "Solution" constitutes 80 to 90% of the pages involved. The problems may be obtained by college and university faculty members and by those in charge of industrial or governmental training programs. They will not be published in a form such that the "Solutions" are readily available to students, so as to preserve the atmosphere of a new and challenging problem situation in the Classroom. Copies of any or all of the problems listed below may be obtained by sending payment or a purchase order to Professor C. J. King, Department of Chemical Engineering, University of California, Berkeley, California 94720. Checks should be made payable to "Regents of the University of California." Overseas orders should add 60¢ per problem for extra handling and postage.

PROBLEMS AVAILABLE

Announcements of Problems CP-1A, 1B, 2, 3 and 4 were distributed to chemical engineering departments in the U. S. and Canada this past winter. Three additional problems have become available since that time. The full list of problems available as of June, 1970, is as follows:

CP-1A.* **Production of Benzene and Xylenes by Hydrodealkylation.** Process Analysis and Synthesis (King). 29 pages ($1.00).

The aim of this problem is to develop an understanding of a chemical process, starting with a simplified flow sheet. The student is asked to determine reasons for the choice of particular operating conditions which have been given in a brief process description. He then must develop reasonable values for other operating conditions which are not given and must consider the possibility of modifying the basic flow scheme in various ways. Finally, a major elaboration of the process is suggested, and the student is asked to synthesize an ordering of process equipment for the new process.

CP-1B. **Simulation of a Hydrodealkylation Plant.** Process Simulation (Alesandrini, King and Foss). 34 pages ($1.00).

This problem is designed to give the student some understanding and familiarity with the requirements of a plant simulation on a computer. The student is asked first to generate a list of independent variables for a moderately complex chemical process. He then must select a sub-group of these variables upon which to base the simulation and present a block diagram of his approach to the solution of the heat and mass balances throughout the process. The selection of independent variables so as to eliminate iterative calculations connected with recycles is stressed.

CP-2.* **Continuous Drying of Air.** Trouble-Shooting (King). 41 pages ($1.25).

This problem involves the analysis of operating data for a fixed-bed, continuous air drying unit. The student is given a smattering of information on the current performance of the unit. On the basis of this he must design an appropriate and discriminating performance test. The results are real data, obtained from a past test on an actual, operating dryer system. From the data the student is asked to identify the source or sources of malfunction and to suggest ways of improving the operation of the unit.

(Continued on page 135)

*CP-1A,-2 appeared in "Chemical Engineering Case Problems," AIChE, New York (1967).

AN OPEN - ENDED COURSE IN CHEMICAL PLANT DESIGN

ChE classroom

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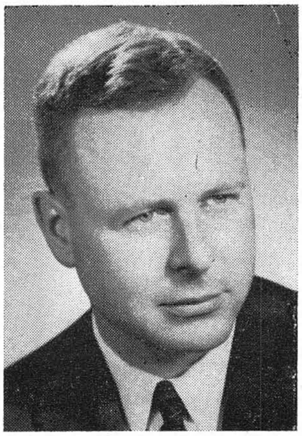
Editors Note: CEE joins the profession in mourning the recent death of Professor O'Connell



Francis P. O'Connell was at the University of Detroit for many years, where he was Professor of Chemical Engineering. Over the past 30 years he was engaged in research, development, process design, project engineering, plant start-up and operations. A graduate of Villanova University, he had the MS and the PhD degrees in chemical engineering from Lehigh University. Dr. O'Connell was a licensed professional engineer in Pennsylvania and Michigan.

Over the years a number of views have been presented on plant design, and each has had its own concept of what design is. Some have concentrated on small problems related to design. Others have concentrated on design calculations. Others have concentrated on the preparation of drawings and specifications. Here at the University of Detroit we have tried to take in the broad concept of design[1, 2], which starts with the conception of a chemical process and ends with the preparation of the drawings and specifications suitable for purchase of equipment and for contractors to make bids on engineering construction. The functions with which the chemical engineer is chiefly interested are emphasized.

CLASS ORGANIZATION

The design sequence consisted of two quarters of ten weeks duration each. In the beginning of the first term a process was assigned, which would consist usually in simply writing a chemical compound, but not necessarily the chemical reaction, for obtaining the compound. The criteria needed for design were worked out during this term. In the second term, then, after the criteria had been worked out through preliminary studies and experimentation, the actual plant design procedure was simulated by the students.

This design sequence was essentially an open-ended course, in that nothing more than a chemical product was assigned to the class. It was a case history approach—the students must decide by what process, chemical reactions, and other modes of procedure that the design should be carried out.

The classes have consisted approximately of twelve to fifteen students who where divided into groups of three to five students each. It is the author's judgment that the optimum group would be somewhere between three and four students. We found that if the group were too small, the students would not be able to cover enough ground to make the assignment worthwhile, and if the group were too large, the more eager students would tend to dominate the group.

DECISION PROCESS IMPORTANT

During the course of this plant design exercise emphasis was not placed solely on calculations, important as they may be. The students had to decide which direction to go, for instance, whether their control valves are to fail open or closed. Here is a list of typical decisions which the students have made:

Whether to use a spray, packed, or plate tower
How much hold-up time for a surge tank
Should reflux be pumped or fed by gravity
Select equipment for separating a liquid-vapor mixture
Should material be shipped by water, road, or rail
Should mounted spare pumps be provided
Mounted spare control valves vs. hand operated by-pass valves

. . . The survey work just described was coupled with experimentation. The students were expected to set up in the laboratory on a bench scale an operation of the process.

Can plain carbon steel be used instead of stainless steel
Is an explosion wall necessary
How large should an escape exit be made
Selection of a fire extinguishing system
Selection of nitrogen, helium, argon, or carbon dioxide as an inert gas
Should spring loaded safety valves or rupture discs be used
Method of removing heat from a reactor

It is hoped that engineering judgment and creativity were developed through this decision making exercise. If a student put forward an idea that was half way reasonable, it was never discouraged, but he was encouraged to discuss his idea with others. Synthesis, as well as analysis, of all concepts had to be emphasized.

ENCOURAGING INITIATIVE AND JUDGMENT

One way to encourage this was to have the class assemble about once a week and give a brief written and oral progress report. This was done in the groups in which they were assigned, so that possibly once a week one member of each group would report on the work progress. This gave him a chance to defend his ideas and the ideas of the group against the criticisms of the other groups. And to a certain degree it developed a healthy sense of competition among the groups. We found that this did not tend to make the groups copy one another. Perhaps this is true because right in the beginning of the course the groups selected a particular path to follow as regards such things as reactions and patented processes, and they tended to deviate from one another as time went on. Nevertheless they could exchange ideas with one another, and this was healthy. It is somewhat of an art, trying to develop healthy discussion among the various groups at the weekly meetings. The teacher must not inject himself too much nor too little.

OPTIMUM CHOICE OF PROJECT

One of the more difficult chores of the teacher is to find a suitable process for the students. The following pitfalls stand out in the choice of an assignment:

1. The right amount of data must be available to the students. If there is too little data available in the literature or otherwise, they are forced to do an undue amount of guessing. If there is too much data available, they are unable to digest it in the time allowed, and they tend to copy previous designs. This would be the case with any of the old heavy chemicals, such as sulfuric acid or caustic-chlorine.
2. The number of technological steps should be optimum. Too few steps would lead to a trivial study. Too many steps would render the project too complex for the time allowed.
3. When laboratory investigations are included in the project, the following limitations prevail:
   a. Safety of the students must be assured.
   b. Pick a process which will allow the students to take meaningful data in the time allowed.
   c. Work is limited by laboratory equipment available.
4. The process must be such that it can be run at a suitable capacity. If the capacity is too small, the students will only be designing pilot plants. We try to shoot for about 100 tons per day.
5. Pick a process that is profitable. This is hard to do, and nothing is more discouraging to the students than to find out that their plant will not be able to make money. Unfortunately today most profitable operations have multidepartment plants and multiplant industries, whereas the students are necessarily limited to one process.

PROCESS DEVELOPMENT PHASE

In the first term, or first phase of the program, the students simulated what happens in the process development stage of plant design in industry. This consisted of learning and practicing a number of techniques associated with the problem. The students had to make a market survey to form some idea, at least qualitatively, of what demand could be expected for the proposed product. The first week the groups were given a chance to go over the process, consult literature, and decide with the best judgment they had available at the time which process they wanted to follow through.

This got them started in a given direction, so that they could go through the entire development and design experience. They then developed a rough flow sheet and went into estimation of fixed and operating capital. Then from capital investment they went to manufacturing cost estimate, profitability estimates, optimization studies, and various economic studies, such as variation of capital cost and profitability with capacity.

The survey work just described was coupled with experimentation. The students were expected to set up in the laboratory on a bench scale an operation of the process. In the ten weeks

. . . it is hoped that in developing this sequence further, we shall be able to expand the use of various optimization and operations research techniques.

or less allotted for this experimental work it has been found that the students had all they could do to merely set up a demonstration of the process itself. This meant that their work was usually confined to reactor studies, which might have given them an opportunity to match mathematical models for the process through the use of kinetic and thermodynamic principles. This also gave them a chance to compare literature data with their actual experimental data, and gave them some conception of problems met in scale-up of processes.

For the most part the mathematical tools used were those the students had in engineering school and consisted mostly of algebra, calculus, differential equations, and error theory. However, it is hoped that in developing this sequence further, we shall be able to expand the use of various optimization and operations research techniques, such as dynamic programming, linear programming, stochastic programming, nonlinear programming, evolutionary operations, game theory, and any other concepts and techniques that may appear in the future.

An attempt was made to have the students go through economic studies a number of times at various stages in the development of the information on the process. This was to allow them to get a feel for the increasing accuracy of their cost estimates as the project progressed. This also allowed them to go through the iterative process of re-evaluating and remodifying their studies, an experience needed in design.

In addition to their written and oral weekly progress reports, which were not allowed to become too time consuming, the students had an interim report and a final report for this process development stage. The interim report was due after about four or five weeks. Format or standards of this report were not made too rigid. The quality of the final report due at the end of the first quarter, or term, was more rigidly controlled to assure that the students had developed all the essential information. Also effort was made to encourage completeness, clarity, usefulness, and workmanlike appearance.

This report contained a process study, including heat and material balances, chemical flow diagrams, and sample calculations. The economic studies mentioned previously were included. Plant location was also shown. Tied in with these studies was a write-up on the experimental findings in the laboratory with an interpretation of the data. Chemical and physical properties of the various materials processed, and needed for design purposes, were required, and salient design problems which the students were able to anticipate were discussed. Also included was a discussion of safety considerations specific to the process. This report ,then, containing the students' conclusions and recommendations, constituted the design criteria which they would use in the second phase of the program concerned with the plant design proper.

DESIGN PROJECT PHASE

In the second term the students, remaining in the same groups that were assigned in the first term, continued with more specific studies on design, where they actually took the criteria they had developed and went through the project work required. This work consisted of roughly two aspects. One aspect embraced project planning and administration. There were instructions on acquisition of equipment and services for the erection and start-up of the plant, on engineering law, erection supervision, and plant commissioning.

. . . An attempt was made to have the students go through economic studies a number of times at various stages in the development of the information on the process.

The other aspect of this term was the process design. This included equipment design calculations. The tools used in these design calculations were very varied and actually drew on every course that the students had in their engineering program. They included calculations in fluid flow, heat transfer, mass transfer, reactor design, economic balances, mechanics of materials, thermodynamics, and many other disciplines. Other disciplines are being introduced as time goes on. For example, the students are showing increasing interest in process control theory. In addition to these design calculations the students were made to simulate, as much as possible, all the services which a chemical engineer and related professions would have to perform on a design project. In their final report they included an engineering work progress schedule with the help of critical path planning. The site selection made in the first phase had to be expanded from general geographical considerations to the specifics of exact location of a site. The material balance had to be worked out in more detail. A more exacting and usable chemical flow diagram was prepared, and the students were shown how to prepare a mechanical flow diagram as well. However, piping drawings, piping specifications, and pipeline designation lists, while discussed, were left optional, because it was felt that this peripheral detailing did not fit in the allotted work time. Selection of materials of construction was included. Equipment specifications had to be included on all process equipment. For vessels this meant drawings showing wall thickness, temperature and pressure requirements, location of nozzles, and other process details, but fabrication details were not required. For other pieces of ready made equipment, such as heat exchangers, pumps, and agitators, they had to fill in standard check lists of specifications with proper back-up information. More complete physical and chemical properties of materials used in the process were included.

In the second term the students continued with more specific studies on design . . .

Operating instructions in reasonable detail were prepared for use by production supervisors. These included a process description, start-up, operation, and shut-down procedures, and maintenance instructions. Diagnostic instructions were prepared for anticipated operational difficulties. Also included were safety instructions suitable for supervising operators to prevent injury and losses due to chemical and mechanical hazards. The students were shown how to prepare an extended equipment list, which also fills a function in acquisition and cost control.

A final economic study was made showing a manufacturing cost estimate in as much detail as possible. This included a final study of return on investment as it varies with the capacity.

Our students did not become involved in more detailed civil, electrical, and mechanical engineering. Their work, for example, would be confined to specifying weight loads without design structures, specifying electrical loads without designing distributions, and specifying steam requirements without designing boiler plants. In

. . . Operating instructions in reasonable detail were prepared . . .

lectures, however, they were made aware of the need and significance of these other engineering professions.

We have made some attempt to have the students work with engineers designing in industry. Success in this direction depends greatly on geographical location. We have had limited success with architect-engineer firms in our area, and we hope to have greater success in the future.

MORPHOLOGY OF DESIGN

The full morphology and anatomy of design was followed in this program to a reasonable degree. The students' operations matched with the seven basic phases outlined by Professor Asimow[1, 2] in his *Morphology of Design.*

CHARACTERISTICS OF PROGRAM

While lectures were given during this program on principles and helpful information useful in design, the students' main exercise was the design of a specific chemical plant. We found that many of these ideas emphasized during the project are difficult to lecture in an interesting manner. Sometimes the students do not see the light until years after they have graduated, at which time they come back and thank the teacher. Lectures on theory and practice of design should be timed, if possible, so that the subjects discussed come up at the same time they occur in the project work.

As regards computers, it is not recommended that it be made into strictly a computer course. The policy has been to encourage the students to use computers when a computerized problem is indicated. This might occur where there are long, detailed iterations required, or where some logical decision network is needed. Computers should not become the be-all and end-all of the program, but rather they should be presented as a valuable tool of serious philosophical portent.

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COMPUTERS AND APPLIED MATH IN THE ENGINEERING CURRICULUM

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THE INSTRUCTIONAL USE of analog and digital computers in today's engineering curriculum is assuming an ever increasing role. This situation has apparently arisen out of necessity, mainly because we tend to emphasize more sophisticated mathematical techniques as the basic key to comprehension and learning. Whereas in the b.c. era (i.e., before computers) undergraduates lived primarily in the "steady-state world", the contemporary student investigates the dynamics of processes in which the "steady-state" assumes its proper perspective as a limiting condition. Therefore the introduction of computers into the curriculum has been a major factor in fostering the evolution of engineering instruction from the art into the science stage.

In developing the full potential of computers and associated mathematics to meet the challenge of present day curricula, the possibility can exist that too much time is devoted to the tools and not enough to the subject matter. Therefore our purpose in this article is to indicate how we at LSU are attempting to bridge such a gap. Toward this end we require fundamental courses in analog and digital computation at the sophomore level, followed by advanced (hybrid) computation and applied mathematics for qualified students. We not only provide instruction on the use of these tools, but encourage such usage throughout the educational program with suitable applications in other coursework.

Employing practical demonstration examples in these advanced courses which submit readily to analysis by a variety of methods from classical mathematics to computer implemented numerical techniques, we stress the problem solving approach in each case. Thus a student's academic training provides the following two-fold methodology to support his professional capabilities:

- He must develop the ability to study a situation, evaluate facts and formulate the problem to be solved based upon sound and fundamental engineering principles.
- Once the problem has been defined quantitatively in engineering terms he must know, and be able to apply the tools with which to effect a reasonable solution.

Obviously one without the other is less than satisfactory.

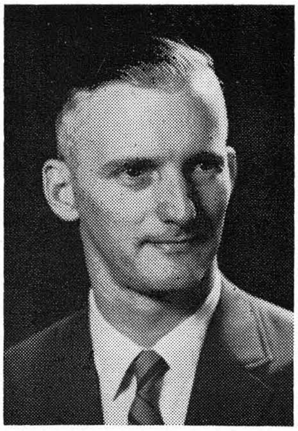
In order to stimulate our students and to gage their progress in adapting to new situations it is instructive to challenge them with a "realistic" problem of a normally non-academic origin. The following example is of this type, having been culled from an article in the literature. We first describe the problem, develop the mathematical model subject to reasonable assumptions, and then outline several solutions applying analytical methods as well as various computer techniques.

STATEMENT OF THE EXAMPLE PROBLEM[1]

In a continuing effort to improve both the quality and performance characteristics of its packaging, a soft-drink corporation desired to consumer field test a newly designed returnable bottle for one of its products. Specifically, it wished to ascertain whether or not the new bottles would have a significantly longer service life than the bottles presently in use.

During the field test new bottles were inserted into the filling line at a specific daily rate over a period of several days. The filled containers (both new type and old bottles interspersed) were displayed for sale as usual in the marketplace. The "empties", returned by the consumer to the market after a reasonable delay period,

*Presented at the ASEE Gulf Southwest Regional Meeting, Texas A&M University, March 22, 1968.



David B. Greenberg obtained his BS, MS, and PhD degrees all in ChE from Carnegie Tech, the Johns Hopkins University, and Louisiana State University, respectively. He is an Associate Professor at LSU in Baton Rouge and is Associate Editor for the journal, SIMULATION. His research interests include analog, digital, and hybrid computation, bioengineering, and transport phenomena.

Larry Morton is currently Director of the Computer Research Center at LSU. He received the BSChE from the Georgia Institute of Technology and the MS and PhD ('65) degrees from Louisiana State University. He has taught courses in computer science, unit operations, and engineering use of digital computers. His interests include computer operations, software, applied mathematics, and unit operations. (left photo)

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were then sent to the plant for refilling. Data collected consisted of a daily count of the new type bottles as they passed the capping station during the bottling process. At this monitoring point both newly inserted bottles as well as bottles that had completed one or more field cycles were included in the count.

In order to obtain a quantitative evaluation of the test results it is necessary to model mathematically the complete cycle, then define and evaluate the performance parameters. To facilitate the development of a mathematical model the following simplifying assumptions are made:

a. The rate of purchase of test containers is directly proportional to the number of these bottles in the marketplace at any time.
b. The losses at the plant and market are negligible compared to the losses sustained in the home by the consumer.
c. There is a constant (average) time delay between purchase and re-insertion of the bottle in the market. This delay accounts for consumption of the product by the purchaser.
d. Time delays in the bottling plant are negligible compared to that by the consumer described in (c) above.

With these assumptions the modified process cycle is described by Figure 1 from which the model is to be derived.

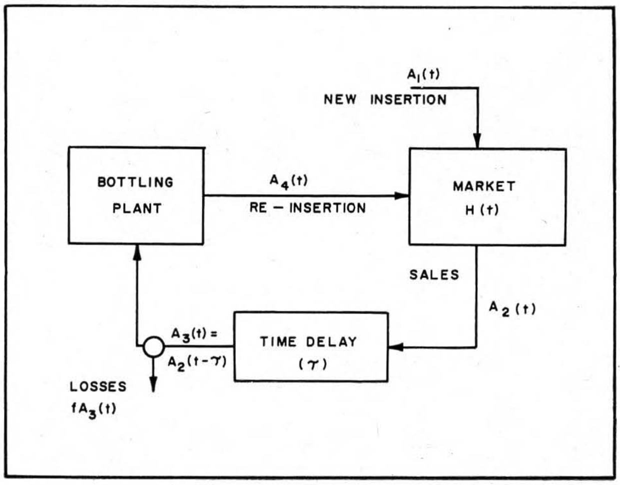

Figure 1. Flow Diagram for the Mathematical Model

DERIVATION OF THE MATHEMATICAL MODEL

An overall material balance for new type bottles on the market yields:

Rate of market accumulation	= −	Rate of sale	+	Rate of re-insertion	+	Rate of new insertion

$$\frac{dH(t)}{dt} = - A_2(t) + A_4(t) + A_1(t) \quad (1)$$

Focusing on the right hand side of Equation (1) the functions are evaluated as:

Rate of sale. If H(t) represents the number of bottles in the market at any time t, then by assumption (a) above

$$A_2(t) = kH(t) \quad (2)$$

where k is the constant of proportionality.

Rate of new insertion. For purposes of the field test, bottles will be inserted at a constant rate C (bottles per unit time) over a given period θ, thus

$$A_1(t) = C \text{ for } 0 \leq t \leq \Theta \quad (3a)$$

and,

$$A_1(t) = 0 \text{ for } t \geq \Theta \quad (3b)$$

Rate of re-insertion. If f is the fraction of bottles lost per cycle, the input to the bottling plant becomes the product of the fraction returned (1-f) and the number of empty bottles returned by the consumer, or

$$A_4(t) = (1\text{-}f)\ A_3(t) \quad (4)$$

But noting that A_3 is evivalent to the rate of sales A_2 displaced in time by the delay period τ, we have

$$A_4(t) = (1\text{-}f)\ A_2(t\text{-}\tau) = (1\text{-}f)\ kH(t\text{-}\tau) \tag{5}$$

The substitution of these terms into Equation 1 yields:

$$\frac{dH}{dt} = -kH(t) + (1\text{-}f)\ kH(t\text{-}\tau) + A_1(t) \tag{6}$$

Equation 6 is the mathematical model describing the process and is characterized by the three parameters k, f, and τ which must be evaluated by field test data. Clearly from the model it is obvious that k is a first order rate constant and the term 1/f represents the average number of cycles a bottle makes in the field before becoming lost. This latter term becomes, therefore, the criterion for comparison between old and new type bottles.

Data (Field test data is given in Table 1)

1/f (old type bottles) $\cong$ 3-4 cycles.

C = 200 new bottles/day inserted into cycle.

$\theta = 5$ days (at a rate of 200/day for 5 days, a total of 1000 new type bottles are put into circulation for the test).

$\tau = 7$ days (this represents the normal time between shopping trips for the average family).

Table 1. Field Test Data

Time (days)	Carrier Count Rate (per week)	(cumulative)
7	0	0
12	56	56
19	164	220
26	183	403
33	178	581
40	140	721
47	145	866

ANALYTICAL SOLUTION

Because of the transport delay term, $H(t\text{-}\tau)$, the solution can be most readily handled by Laplace transform methods. It should also be noted that Equation 6 lends itself to solution by finite difference methods on the digital computer by which the authors of the original article obtained their results. We define the Laplace transform of each term and make appropriate substitutions in Equation 6 to obtain the following algebraic expression:

$$sh(s) = -kh(s) + \alpha e^{-s\tau}h(s) + \frac{C}{s}(1-e^{-s\theta}) \tag{7}$$

where $\alpha = (1-f)k$, and $H(0) = 0$ for this situation

Equation 7 when solved for the transformed dependent variable h(s) becomes:

$$h(s) = \frac{\frac{C}{s}(1-e^{-s\theta})}{(s+k-\alpha e^{-s\tau})} \tag{8}$$

The analytical solution follows by first rearranging, then expanding Equation 6 using the binomial theorem, and inverting term-by-term to give:

$$H(t)=\frac{C}{k}\sum_{n=0}^{\infty}(1-f)^n e^{-k(t-n\tau)}\left\{e^{k\theta}\sum_{J=0}^{n}\frac{k^J(t-n\tau-\theta)^J}{J!}u(t-n\tau-\theta)-\sum_{J=0}^{n}\frac{k^J(t-n\tau)^J}{J!}u(t-n\tau)\right\} \tag{9}$$

where $u(t-n\tau-\theta) = \begin{cases}0 \text{ for } t \leq n\tau-\theta \\ 1 \text{ for } t > n\tau-\theta\end{cases}$ is the Heaviside unit function.

The complete solution to this problem requires that parameter 1/f, the average number of cycles per bottle, be evaluated. To obtain this term we must first compute both $H\tau = H(t\text{-}\tau)$, the time displaced bottle concentration in the market, and $Hc(t\text{-}\tau)$ the cumulative total of bottles progressing through the bottling plant. By calculating the absolute value of the difference between $Hc(t\text{-}\tau)$ and He the cumulative field test data, an error function E(t) can be obtained. The correct values of k and f are therefore determined by varying these parameters systematically so as to minimize the criterion E(t) over the entire test period. With Equation 9 as a starting point it is evident that such a task can be quite formidable in terms of time even for the digital computer. A more reasonable approach using statistical-numerical methods follows:

DIGITAL COMPUTER SOLUTION

We first define an expression for the cumulative total of bottles in the bottling plant in terms of the bottle concentration $H(t\text{-}\tau)$

$$Hc_i = \sum_{j=1}^{i}(1-f)\ kH(t_j-\tau) \tag{10}$$

where the summation ranges over daily values of concentration up to time t_i. As before the error function is calculated as the difference between Hc, the analytical, and He, the cumulative field test data. We require values of k and f to minimize E(t) summed over all data points.

$$E(t) = \sum_{i=1}^{m}(He_i-Hc_i)^2 \tag{11}$$

where the index m represents the total number of data points collected in the field test and E(t) is a function of f and k. By the method of least squares a pair of equations may be derived by differentiating E(t) with respect to both f and k and setting the results to zero. Before differentiation Equation 11 is expanded by Taylor's series about some point z. We then differentiate

E(t) with respect to each parameter, equate the resulting partials to zero, and obtain the following linear equations:

$$\sum_{i=1}^{m}\left(He_i - g_{i,z}\right)\frac{\partial g_{i,z}}{\partial f} = \Delta f \sum_{i=1}^{m}\left(\frac{\partial g_{i,z}}{\partial f}\right)^2 + \Delta k \sum_{i=1}^{m}\left(\frac{\partial g_{i,z}}{\partial f}\right)\left(\frac{\partial g_{i,z}}{\partial k}\right) \quad (12a)$$

$$\sum_{i=1}^{m}\left(He_i - g_{i,z}\right)\frac{\partial g_{i,z}}{\partial k} = \Delta f \sum_{i-1}^{m}\left(\frac{\partial g_{i,z}}{\partial f}\right)\left(\frac{\partial g_{i,z}}{\partial k}\right) + \Delta k \sum_{i=1}^{m}\left(\frac{\partial g_{i,z}}{\partial k}\right)^2 \quad (12b)$$

where $\triangle f = f - f_z$ and $\triangle k = k - k_z$.

Initial estimates f_z and k_z of the unknowns f and k at some arbitrary point z, but sufficiently close that convergence will occur, are used to evaluate all sums in Equations 12, from which Δf and Δk are computed. Application of these incremental changes results in estimates f_{z+1} and k_{z+1} which should converge eventually to f and k.

By taking derivatives of Equation 10 with respect to the parameters f and k we obtain the following expressions:

$$\frac{\partial g_{i,z}}{\partial f} = \frac{\partial Hc_i}{\partial f} = -C\sum_{j=1}^{i}\left[\sum_{n=0}^{\infty}(n+1)(1-f)^n\left\{u_j - v_j + e^{-ka_j}\left(e^{k\theta}v_j\alpha_j - u_j\beta_j\right)\right\}\right] \quad (13a)$$

$$\frac{\partial g_{i,z}}{\partial k} = \frac{\partial Hc_i}{\partial k} = C\sum_{j=1}^{i}\left[\sum_{n=0}^{\infty}(1-f)^{n+1}e^{-ka_j}\left\{v_j e^{k\theta}\left[\sum_{r=1}^{n}\frac{k^{r-1}b_j}{(r-1)!} + \alpha_j(\theta - a_j)\right] - u_j\left(\sum_{r=1}^{n}\frac{k^{r-1}a_j^{\,r}}{(r-1)!} - a_j\beta_j\right)\right\}\right] \quad (13b)$$

where $\alpha_j = \sum_{r=0}^{n}\frac{k^r(t_j - n\tau - \theta)^r}{r!}$; $\beta_j = \sum_{r=0}^{n}\frac{k^r(t_j - n\tau)^r}{r!}$

$a_j = t_j - n\tau$; $b_j = t_j - n\tau - \theta$

Heaviside unit functions:

$u_j = u(t_j - n\tau)$; $v_j = u(t_j - n\tau - \theta)$

Equations 12 and 13 are in a form which permits a digital computer solution. Given m cumulative field test data points and reasonable initial estimates for f_z and k_z, the partials in Equations 13 may be calculated for each point. Cross products of these partials at each point are accumulated according to Equation 12.

In order to test the convergence of this method, initial values f_z and k_z were taken at values given in Table 2 following. This Table also shows the final approximations f and k and the number of iterations required to achieve 3-place accuracy. The time required on an IBM 7040 computer for each case is given.

Table 2. Convergence Values, Digital Solution

Initial Estimates		Iterations Required	Time Required	Final Approximation	
f_z	k_z		sec	f	k
.058	.0293	22	61	.1636	.03701
.239	.043	21	59	.1643	.03704
.1	.01	26	72	.1636	.03701

Today's engineer must have a solid foundation in applied math to avoid absolescence in the light of advances in science and engineering . . .

In all cases above the computing time to converge to a satisfactory result was on the order of one minute. Certain steps could be taken to speed up convergence, but unless the problem is one which would be used frequently, there is little incentive for the extra programming effort. (Program documentation and sample problems are available from the authors for interested readers).

ANALOG COMPUTER SOLUTION[2]

From the student's point of view analog solution methods are often the most interesting, for the system model is programmed directly on the computer which responds (hopefully) to perturbation as does the real physical system. Furthermore, in this case there is considerable man-machine interaction, because the student forms an integral part of the information feedback loop.

In programming this problem for the analog the basic equations to be considered are Equations 6, 10, and 11. We perform the task of magnitude and time scaling and rewrite them in integral form below.

$$[.01H] = -\int_0^t\left\{10^{-1}(10k)[.01H] + 10^{-1}\langle 10k(1-f)\rangle[-.01H\tau] + (10^{-3}A_1)[-10]\right\}dt \quad (14)$$

$$[.01Hc] = -\int_0^t 10^{-1}\langle 10k(1-f)\rangle[-.01H\tau]\,dt \quad (15)$$

$$[e] = -\left\{[-.01Hc] + [.01He]\right\} \quad (16)$$

$$[E] = -\int_0^t\left[-\frac{e^2}{10}\right]dt \quad (17)$$

The parameter [e] represents the instantaneous difference between model and experimental value of the cumulative total of bottles, and [E], the criterion function, is proportional to the accumulated total error between these terms.

In the mechanization of these equations an electronic switch, triggered by the polarity change of a ramp function signal, was used to generate the discontinuous function $A_1(t)$. A variable diode function generator provided an approximation to the experimental field test data, He, and the transport delay was simulated by a fourth order modified Padé circuit. As indicated by the output curve, $H(t-\tau)$ of Figure 2, this approximation is quite adequate for the low fre-

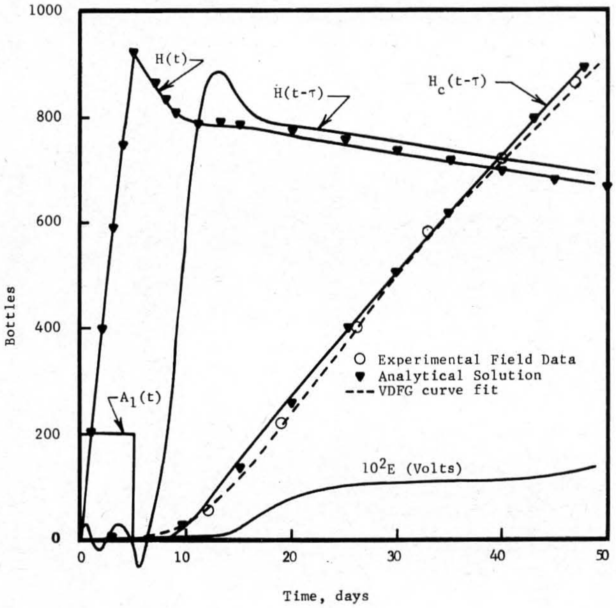

Figure 2. Output Curves, Final Run

quencies involved here (time scale for this example was chosen as 1.0 seconds of compute time per day of problem time).

The analog procedure, a global search technique, is relatively straight forward. Computing in the repetitive operation mode, the parameters k and f, each isolated on a potentiometer, are varied in alternative fashion, one discretely and the other continuously and E(t) values are obtained visually on the oscilloscope. When an approximate absolute minimum has been established, a few real time computer runs can be made to obtain a more accurate value of the criterion function. Three place accuracy in the answer is readily attainable with a digital voltmeter.

DISCUSSION OF RESULTS

The analog output for the final real-time run is presented in Figure 2. For purposes of comparison the analytical solution which was evaluated on the digital computer has also been included. As the figure shows both results predict accurately the peak of the H(t) curve and the slight dip beyond that point. In general, the agreement between these two results is excellent.

It is also apparent that the analog and analytical solutions for the cumulative field data, Hc(t-τ) curve, also show close agreement. In comparing these results with the analogous experimental data points also plotted in Figure 2, we observe that for these final k and f values the mathematical model provides a reasonable curve fit except initially where the rate of slope change is greatest. The difference here is due in part to the imperfect nature of the transport delay simulation circuit employed; the initial transients of which are clearly evidenced on the curve of Figure 2.

A comparison of the final parameter values is given in Table 3. The approximately 7% lower value of the parameter f obtained from the analog solution arises from the fact that experimental field data points were fit by a series of 10 straight line segments with the VDFG. On the other hand an almost exact fit using a 7th degree polynomial was employed to fit the data for the analytical solution. Despite these differences the final result in all cases suggests that the new type containers have a service life of more than 50-75% longer than the original carriers.

Table 3. Comparisons of Final Parameter Values

Parameter	Analog	Digital	Analytical
k	0.036	0.037	0.037
f	0.152	0.164	0.163
1/f	6.0	6.1	6.1

SUMMARY

In this article we have attempted to show by a specific example how digital and analog computers are being used in the undergraduate engineering curriculum at LSU to enhance instruction in applied mathematical methods. This particular problem, although relatively elementary from a mathematical point of view, has been useful in developing and exercising student proficiency in the following areas:

- The use of Laplace Transform techniques to obtain an analytical solution.
- The use of a statistical numerical method (least squares) to effect a digital solution.
- Finite difference methods (presented in the original publication) for the digital computer.
- Digital programming logic for the analytical as well as the two numerical methods.
- Analog programming techniques: the use of analog logic, switching, and other non-linear equipment, the development of a method of transport delay simulation.
- The use of a simple optimization method.

Analog and digital computers are needed in today's curriculum because we emphasize more sophisticated math techniques as the key to comprehension and learning.

Of equal importance from an instructional standpoint in the fact that this exercise, of an interdisciplinary nature, is a very practical industrial problem that any professional engineer might encounter. It follows therefore that the problem is completed when an interpretation of the mathematical solution invokes a practical engineering decision. We have found with this problem as with others which we have developed, that this "practical flavor" or realistic aspect has been an important factor in eliciting a most favorable response from among our students. As a follow-up to the problem presented here it was interesting for our students to discover that similar mathematics were reported by T. Wood[3], who investigated first order irreversible chemical kinetics in a series connected well-mixed and tubular reactor system.

REFERENCES

1. Barnes, B. G., R. E. Fuchs, and R. A. Somsen, TAPPI, **50**, 72A (1967).
2. The analog computer solution: Simulation, **Vol. X**, No. 4, 157 (April 1968).
3. Wood, T., Nature, **191**, 589 (1961).

KING: CASE PROBLEMS

(Continued from page 125)

CP-3. **Removal of Water Vapor in Freeze-Drying.** Process Synthesis (Kumar and King). 89 pages ($2.75).

This problem requires that the student generate and give a rough, evaluative screening to different approaches to the removal of water vapor which is being continually generated in a vacuum chamber, in this case a freeze-drying process. Initial attention is given to the conception of various techniques for removing water vapor. Then preliminary analyses are made of the proposed schemes to check the feasibility of each process, to gauge its requirements in terms of materials and energy, and to determine the merits and drawbacks of the proposal.

CP-4 **Desalination by Reverse Osmosis.** Process Synthesis and Optimization (Thompson and King). 60 pages ($2.00).

The student is presented with the basic physical concepts underlying reverse osmosis and is given some indication of the difficulties which may arise and the factors to be compromised in a reverse osmosis desalination process. The principal problem is to determine the best configuration of a reverse osmosis unit so as to achieve minimum energy consumption. The student must recognize the mechanisms by which design parameters influence pressure drop and water flux. He must ascertain which decisions can be made on the basis of qualitative or common sense thinking rather than through the optimization of formal mathematical equations. Finally, he can determine optimum values of the remaining decision variables through either mapping or a formal optimization procedure.

CP-5. **Sulfate Removal from Brackish Water.** Process Synthesis (Forrester and Lynn). 50 pages ($1.50).

This problem concerns the synthesis of a process which removes sulfate from a brackish water supply and which permits the recovery of both the potable water and its previous mineral content. The student is given several existing processes with which to work and is asked to combine them in the best way. Several different elements of process engineering are involved, including development of process flow sheets and mass balances, consideration of the heat requirements of different processing sequences, thermodynamics of reactions in aqueous solution, and consideration of pollution potentials during a process design.

CP-6. **An Evolutionary Problem in Process Simulation.** Process Simulation (Grens). about 55 pages ($1.75).

In this problem a number of basic aspects of process simulation are incorporated in a series of computer implemented projects, which evolve from basic equilibrium vaporization calculations to simulation of a process with material and enthalpy recycle loops. The problem is based upon a hydrocarbon absorber-stripper system, with absorber and stripper each having only one stage. First the student is asked to develop efficient procedures for equilibrium flash computations. Then he must develop simulations for the absorber-stripper system, with alternative convergence techniques being used and compared. Finally interstream heat exchange is added to the problem, and simulations of the dual loop system (material and thermal recycle loops) using both direct substitution and convergence accelerating techniques are sought. Development of efficient modular simulation programs is stressed throughout.

CP-7. **Removal of Inerts from Ammonia Synthesis Gas.** Process Synthesis and Analysis (Alesandrini, Sherwood and Lynn). about 60 pages ($1.75).

The purge of methane and argon from ammonia synthesis recycle gases causes a substantial simultaneous loss of hydrogen and nitrogen. This problem pursues the question of somehow obtaining a partial or complete separation of methane and argon from the other gases, by taking advantage of the unusual vapor-liquid equilibrium behavior of the system of these gases mixed with ammonia. Successively better process modifications are developed and are explored through energy and mass balances, followed by preliminary equipment sizing and economic evaluation. A computer calculation of the behavior of an absorber-stripper may be included at the discretion of the instructor.

There are more than 100 billion barrels of potential new oil on the North American continent. But it will have to be dug—not pumped—out of the ground. It's in the form of low-grade hydrocarbon solids. Yet, the world needs so much more oil in years to come that Atlantic Richfield is already working on ways to extract it and get it moving. Projects like this take imagination and fresh viewpoints. The kind that come from young innovators like yourself. We need you—and your kind of ideas—to keep making great things happen. Talk to our interviewer when he's on your campus. Or write to: Manager Professional Recruitment, 717 Fifth Avenue, New York, N.Y. 10022.

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ChE problems for teachers

Professor R. R. Davidson of Texas A&M University comments on Professor A. J. Brainard's problem in the Spring issue of **CEE.**

After hearing Dr. Brainard's talk "Does the Entropy of a Compound System Always Reach Its Maximum?" at the February meeting of the AIChE in Atlanta, I gave my graduate thermo class a quiz containing the following pair of questions:

1. Given the first and second law and that internal energy and entropy are state functions, show that for any process in an adiabatically isolated system $\triangle S \geq 0$.

2. Given a system comprised of two chambers separated by a freely moving adiabatic wall or piston. The entire system and each chamber is adiabatic. Both chambers contain gases, but the pressure is higher in Chamber I and the piston is kept from moving by a stop (Brainard's Figure 1). If the stop is removed so that the piston can move freely until it comes to rest with the pressures in the chamber equalized, will the change in entropy be less than, equal to, or greater than zero in

(a) The entire system

(b) Chamber I

(c) Chamber II

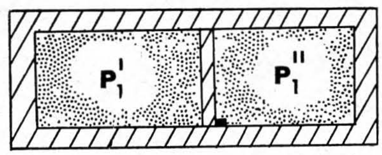
(d) Is the entropy of the entire system necessarily at a maximum?

The answer to (a), (b), and (c) follows directly from the results of Problem 1. Since the initial pressures in Chambers I and II were unequal, the process was irreversible, and since the entire system as well as Chambers I and II were each an adiabatically isolated system, the entropy change in each case was greater than zero.

The answer to Problem (d) is no, because the maximum entropy is reached when thermodynamic equilibrium is reached and this system is not necessarily in thermodynamic equilibrium because the temperatures in the two chambers are not necessarily equal. The word necessarily is used because one might, by manipulating the initial temperatures, obtain a final state in which the temperatures are equal.

The final state in this problem cannot be obtained by thermodynamics. Given the weight of the piston, its coefficient of friction, the dampening factor for the gas and its PVT properties, the final position of the piston could be calculated, but this is a problem in mechanics,

$P_1^{I} > P_1^{II}$



not thermodynamics. Thermodynamics can only say that the final entropy is greater than the initial value and less than the value that could be calculated if heat could flow freely through the piston giving a uniform temperature throughout the system.

I think it should be stressed that our inability to obtain a thermodynamic solution for the final adiabatic state is not due to a lack of thermodynamic rigor, but to the fact that the solution does not lie within the realm of thermodynamics. In general thermodynamics can only give answers for equilibrium states and this means, among other things, that the temperature is uniform throughout the system.

After the quiz a student posed a good question. **What if different gases were on each side of the piston, wouldn't we have to let the gases mix before thermodynamic equilibrium could be obtained?** The answer is yes and no. It is true that if we punched a hole in the piston the entropy would further increase. While we might consider this final state to be the global maximum of the entropy, the final state without mixing, but at uniform temperature, is a local maximum having a thermodynamic solution. It is unlike the state in which only mechanical equilibrium is reached for which there is no thermodynamic solution at all.

The system at uniform temperature is at a definite state before and after the hole is punched in the piston, and so the entropy of adiabatic mixing can be thermodynamically calculated. However, with the adiabatic piston, the final temperatures are undefined because the internal energy of the total system, though known and constant, can be distributed in an infinite number of ways. Thus we see that imposing an impermeable wall is not like imposing an adiabatic wall.

It was interesting to note that while many students missed part (d), a number also missed part (b) and (c). They seemed intuitively to want to conserve entropy, and they found it hard to believe that it increased on both sides of the piston even though they had just proved it in Problem 1.

AN UNDERGRAD CHE LABORATORY

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Dr. Charles C. Peiffer graduated from Lehigh University in 1951. He worked with Atlas Chemicals and the U. S. Army before joining the Petroleum Refining Laboratory of Penn State in 1956. He was awarded the PhD degree in 1962 and joined the faculty at Penn State in 1963.

Various views have been presented about the ultimate educational aspects of an undergraduate Chemical Engineering Laboratory course. In most cases, the questions of prime importance involve

- The size of equipment to be used?
- Should all experiments be functioning normally?
- At what point in the curriculum should the course be taught?
- What theoretical aspects should be covered?
- The type of reports required and the basis for grading?

Some chemical engineering faculty members feel the laboratory should involve equipment of pilot plant size mainly to provide the student with a feeling for the problems he may encounter in industry. Yet, does the student actually benefit from operating equipment requiring a full laboratory period to attain steady state conditions? Or would the student obtain a better insight to the problems he will evenually face in industry if sufficient data can be obtained to enable him to tie together the loose ends of theory dangling in his subconscious?

Other faculty members feel that the equipment should contain "bugs", thus requiring the student to determine the reasons for poor performance. Thus, before the student can obtain meaningful data he must locate and fix the trouble. This procedure again may consume much of the available laboratory period and result in insufficient data for writing a meaningful report on the experiment.

Another method would be to have the equipment functioning normally at the outset of the experiment. After the student has obtained sufficient data, the faculty member can demonstrate the effects of these so called "bugs." The student, if confronted with similar problems at a later time, would then know the necessary steps to be taken to correct the malfunction. In this way he not only ties together loose ends of theory but also obtains some practical experience.

Some ChE Departments conduct their laboratory courses during the summer vacation period between the junior and senior years. A program of this type will permit the utilization of larger and more complex equipment by operating such units continuously for 16 to 24 hours. However, the same principles can be covered in smaller equipment in two eight-hour laboratory periods. This would then leave the summer between the junior and senior year available to the students to obtain summer employment in industry. Since chemical engineering is so diversified, such industrial experience is invaluable to the student in helping him decide which area of specialization would best meet his interests. Other departments incorporate the laboratory with the unit operations courses, thus limiting the experimental procedures covered to the theory covered in these courses. If the majority of theoretical aspects covered in the ChE curriculum are to be incorporated in a laboratory program, a course separate from the theory courses is most suitable. A ChE laboratory could be given during the senior year in two separate courses. This would permit sufficient time to incorporate experiments pertaining to the unit operations courses, as well as kinetics, process dynamics, and other theory courses.

After having been in charge of an undergraduate ChE laboratory course for the past six years, under varying instructional conditions and while utilizing various sizes of equipment, this author has developed the following views.

During the first two years, the writer while in charge of the laboratory, required each student to perform a total of sixteen experiments related to the unit operations theory courses. These experiments were performed during two ten-week terms with the students meeting two four-hour laboratory periods for each experiment.

Some of the equipment was of sufficient size and complexity that two-thirds of each laboratory period was spent obtaining steady-state conditions. Other experiments were performed on smaller pieces of older equipment in which certain "bugs" would inherently be present. As a result of both types of equipment, it was impossible for the students to obtain more than one set of data in each laboratory period for these particular experiments. Thus, the students simply became familiar with the operating procedures and gained no insight as to the optimum operating conditions. How can a student write a meaningful report with one set of data?

Early in 1965 plans were made for an addition to the then existing facilities of the ChE Department which had been completed some five years earlier to accommodate the graduate program. The ChE Laboratory, previously housed in a classroom building separate from the ChE facilities was to be located in the new addition. It was necessary to plan a room of sufficient size to house the experiments in use, or to design new experiments for the allotted space, which would adequately coincide with the theory covered in the unit operations and related courses. The latter approach was followed. The new unit was completed in August of 1968 with the first laboratory course taught the fall term of 1968.

During the interim period between 1965 and 1968 new experiments were designed with their incorporation into the then existing program. The older experiments were first replaced, at the rate of two to three each calendar year.

Concurrently, it was decided to have the students perform the required experiments during one eight-hour period rather than two four-hour periods. This change allowed the students to obtain more sets of data on the larger and more complex equipment. However, in some cases, the data were yet of insufficient quantity for the student to determine optimum operating conditions. It was, therefore, decided to design equipment on a smaller scale where possible, and less complex. When the complexity or size of the experiment could not be lessened, two eight-hour periods were allowed for it.

These changes coupled with the new equipment, relatively free of "bugs," permitted the students to obtain sufficient data to make a complete analysis of the situation confronting them.

The program now in effect consists of two two-credit courses taken during the senior year. The first course involves the following experiments that can be completed in one eight-hour laboratory period and covers areas of chemical engineering involving (1) vapor-liquid equilibrium, (2) filtration at constant rate and constant pressure, (3) nucleate and film boiling, (4) continuous transport of solids, (5) catalytic dehydration of an alcohol combined with analysis of products by gas chromatography, Figure 1, (6) analog computation, (7) batch reaction kinetics, and (8) continuous stirred tank reaction systems (Figure 2).

The second course involves experiments performed during two eight-hour periods and covers areas of chemical engineering involving (1) velocity profiles and pressure drop studies, (2) mass transfer coefficients by use of wetted wall columns, (3) liquid-liquid equilibrium and extraction, (4) distillation in a sieve tray column, (5) process dynamics (Figure 3), (6) heat exchange coefficients for both heating and cooling in 1-2 pass shell and tube heat exchangers under laminar and turbulent flows, (7) economy studies in a multiple effect evaporation system, and (8) batch and continuous stirred tank reactor systems.

In the first course each student performs all of the listed experiments with the results reported by each student in the form of a technical letter (short form report).

In the second course each student performs four of the two-period experiments. Since a required course on reaction kinetics appears in the curriculum, the experiment on reactor systems is a part of both laboratory courses so that each student performs this experiment. Each individual presents the results in a long form or formal report. The schedule of experiments is so arranged that duplication of theory is not encountered. As an example, a student performing the distillation experiment will not do the one on extraction. Also, a student who has not taken the theory course in process dynamics does not perform this experiment.

The program consists of two two-credit courses taken during the senior year . . . the first course requires eight eight-hour experiments . . . the second course allows the student to elect four sixteen-hour experiments . . . Both technical letters and formal reports are required.

With the various changes made during this five-year interval, both instructional and equipment wise, it was found that the quality of the reports improved tremendously. It was also evident that the students' attitude toward the laboratory improved greatly when it was possible for them to obtain sufficient data to apply the theory they had previously studied. The overall result was excellent laboratory performance, thus allowing the laboratory instructors to place more importance on report writing for determining overall performance in the course.

In summary it is felt that

- The equipment in an undergraduate ChE laboratory should be of a size and complexity to allow the student to obtain sufficient data in the allotted time so that he can properly analyze the situation confronting him.
- The laboratory course should be a separate entity in the curriculum and should contain a reasonable variety of experiments to illustrate the majority of theoretical aspects covered in the ChE curriculum.
- Both technical letters (short form reports) and formal reports should be required with prime importance for overall performance being placed on report writing since poor laboratory performance is directly reflected in the final report.

APPENDIX

1. Experiment on Catalytic Dehydration and Analysis by Gas Chromatograph

An alcohol is catalytically dehydrated in an electrically heated tubular reactor packed with a basic alumina catalyst. Determinations are made at two temperature levels and three different liquid hourly space velocities to determine the effect of each variable on reaction rate.

Per cent conversions are determined by various analytical methods with the final analysis of products formed being determined by gas chromatographic analysis.

2. Experiment on Continuous Stirred Tank Reactor Systems

This is part two of an experiment on the saponification of ethylacetate with sodium hydroxide. Two five-gallon polyethylene storage

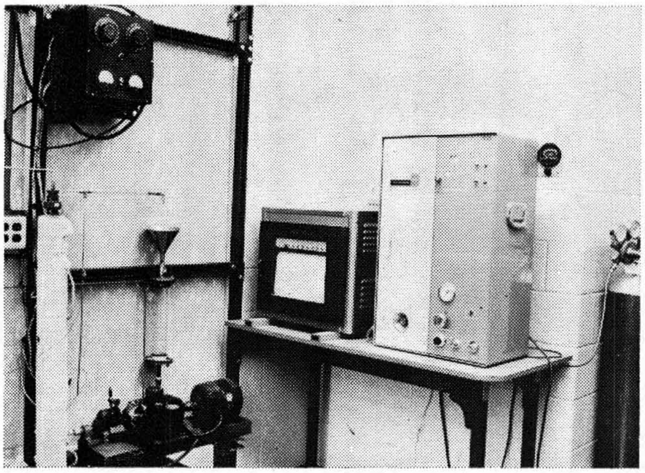

Figure 1. Equipment for catalytic dehydration.

tanks contain the two reactants which flow by gravity through the respective rotameters into the first stirred vessel. The overflow from reactor one can be directed to the drain or to the

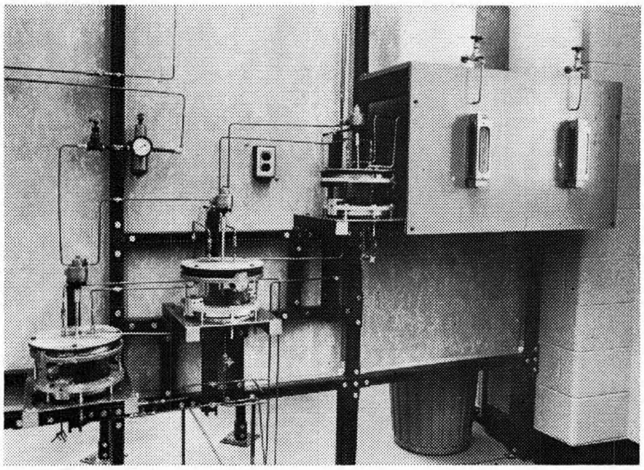

Figure 2. Continuous stirred tank reactor.

second reactor. Similarly the overflow from reactor two can be directed to reactor three or to the drain.

The first week's work involves the determination of order of reaction, the reaction rate constant, and the energy of activation by obtaining batch data at three different temperatures. The results are used to predict what should happen in a continuous flow system, as the one depicted above, at a flow rate and temperature selected by the students.

3. Experiment on the Process Dynamics of Liquid Level Control

The dynamics involved in liquid level control of a simple one-tank system, and a two-tank system involving interaction are investigated.

The students first determine the relationship between proportional band setting and controller sensitivity or proportional gain. The transfer functions for the transducer (converts liquid height to psi), the control valve, and the process are then determined.

After all transfer functions are determined, the student then proceeds to determine the best mode or combined modes of control which will result in bringing the system to the desired operating level in the least amount of time with minimum overshoot and oscillations.

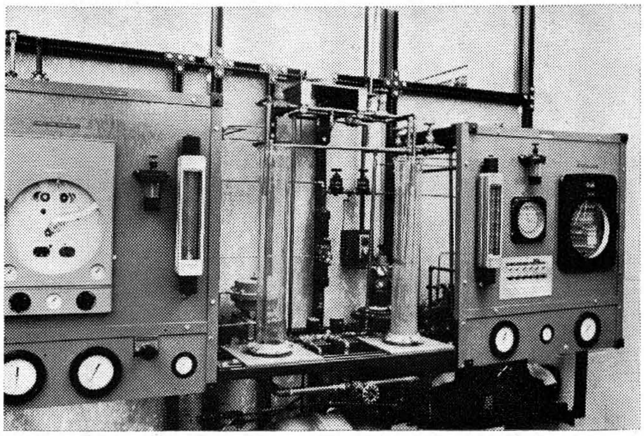

Figure 3. Liquid Level Control.

The appropriate control equations are obtained from the complete process block diagram and experimental results are compared to theoretical predictions.

4. Experiment on Heat Transfer Coefficients

Two 1:2-pass shell and tube heat exchangers are interconnected to permit procurement of the overall heat transfer coefficients resulting from a 1:2- or a 2:4-pass shell and tube heat exchanger.

Individual inside and outside coefficients for both heating and cooling can be calculated from the data obtained in the experiment. The students can also determine the correction factors involved between true countercurrent flow heat exchangers and multipass exchangers.

5. Floor Plan of Laboratory

The new Penn State laboratory occupies a 100 ft. by 30 ft. room, partitioned into cubicles 10 ft. by 8 ft. constructed from transite sheeting and Unistrut channels.

ChE International

AN ASSISTANCE PROGRAM IN ECUADOR

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George Klinzing received his BS degree in Chemical Engineering from the University of Pittsburgh and his MS and PhD from Carnegie-Mellon University. He spent three years teaching and consulting in chemical engineering at Central University in Quito, Ecuador. His interests are transport phenomena and engineering education in and technology transfer to developing countries.

At the present time there are three universities that are offering degres in Chemical Engineering in Ecuador. There is one other university that offers a degree in industrial chemistry based on the European system. Two of the schools of chemical engineering are located in the capital city of Quito and the other is in the port city of Guayaguil. Having two schools in the same city producing chemical engineers in a country where the chemical industry is next to nonexistent is a bit unusual and one may question why this development. The Politecnic University in Quito is under the UNESCO auspices and most of the advisors who have served there have been Europeans. The program of assistance to Central University was one of the total development of the University. To have left the School of

Chemical Engineering from this program would have had severe consequences.

CENTRAL UNIVERSITY

Central University has a student body of some 5,000 students. Most of the classes are held in the early morning from 7 to 9 a.m. and in the late afternoon from 5 to 9 p.m. This is necessary since the majority of the students and professors are part-time. The part-time situation arises from an economic need. Some of the students must work to live and the professors must augment their meager University salaries by additional jobs. For the most part teaching at the University is a highly prestigous matter. The professors who thus elect to teach in the University are usually concerned with the education of students.

In Chemical Engineering the number of part-time students is not very great. Most of the students in Chemical Engineering are full-time although the faculty does not operate on a full-time system.

STUDENTS

Students in Latin America play a more active role in University affairs than students in the United States. At Central University in each faculty of the University there is a student representative on the University Council, and each of these students has a vote on an equal basis with deans and administrators in establishing University policy even in financial transactions and possibly the hiring and firing of professors. Temporary closure of the University for a period ranging from a few days to a few weeks because of political instability is anticipated at least once a year.

CHE AT CENTRAL UNIVERSITY

In 1963 when the University of Pittsburgh began its contract with Central University, the School of Chemical Engineering was a part of the Faculty of Natural Sciences and Chemistry. The other components of this faculty were the School of Geology and Mines, the School of Biochemistry and the School of Pharmacy. The arrangement of schools in this faculty seems like an odd combination but this type of arrangement often arises in Latin America. The School of Pharmacy preceded the others in age and thus when chemical engineering was enacted as a school in 1950 the obvious place to put it in the university structure was where the chemists were. In the majority of Latin America Chemical Engineering is a relatively new field. In 1966 the Schools of Chemical Engineering, Civil Engineering, Geology and Mines were combined into one Faculty of Engineering. The Faculty is headed by a dean and each school is supervised by a director.

The program of study prior to 1966 for Chemical Engineering required six years. The first year of study was a preparatory course intended to make up the deficiencies that existed in the student's preparation in the secondary schools. Chemical Engineers in developing nations do need a different program from those in the developed countries although a certain basic core is needed in order to call a program Chemical Engineering.

In viewing the curriculum at Central University as well as at any of the Latin American Universities one must continually keep in mind that state of the technology of the developing nations is different than that of the developed. The engineer in the developing nations must be educated along avenues that are much broader so that he will be able to cope with more of the total problem. The student must employ his ingenuity to a greater extent when he leaves school in order to apply the principles of his engineering education to his developing country.

The engineering student must know something about the laws of his country in relation to business practices, and accounting and managerial abilities are additional areas where the student must be proficient. He will have to be able to deal with many unskilled laborers, some not even speaking his language.

One area that must be emphasized to the student for progress in the developing countries is the utilization of products natural to the country. Food processing and preservation is essential for development. This is first necessary on a national basis then with time creating an international market for the products. Extraction of chemicals and drugs from local vegetation is a very profitable endeavor and provides an economic international market almost immediately. A very thorough and complete geological study must be done for the exploring of new areas for production.

CURRICULUM MODIFICATIONS

Modifications were enacted in the curriculum of the School of Chemical Engineering after three years of meetings, discussions and debates on the relative merits of most every point and professor. The number of total hours present in the curriculum was decreased. The program was also modified in order to present courses in a much better manner with the preparation of syllabi and detailed laboratory programs with assistants to aid with the latter. One major change was the regulation regarding the thesis requirement and graduation procedure. The old regulations required that the student on completion of his course of study of six years would prepare a thesis on a subject that was usually an economic and engineering analysis of the production of a material natural to Ecuador. Because of this long and involved process very few students who finished their courses "egresados" ever completed the tedious remaining tasks and thus never completed the requirement for the title of "ingeniero." This requirement was eliminated for the more practical program where the student in his last year of study would choose a thesis topic and an advisor under whom he would work. At the finish of the thesis he would have an oral examination. At a prescribed time the people completing the above requirement had a graduation. During the first of these graduations eleven people received their degrees. Most of these had finished their course work within the previous six years. This practical procedure thus permits in principle the assimilation of the graduate into the technical structure of the country the quickest way possible after graduation.

EQUIPPING THE FACILITIES

The equipping of new facilities was accomplished via the funds of AID under the contract of the University of Pittsburgh and Central University. Along with this grant fund Central University also received a loan from the Interamerican Development Bank. These funds were used to develop the laboratories and libraries of the School. The equipment purchased represented a distribution of experiments in Unit Operations, Transport Phenomena, Control and Kinetics. Equipment for analysis, machine shop and expendable items such as glassware, chemicals and solvents were also bought. All the books in Spanish in the field of Chemical Engineering and related fields were purchased. It might be noted that this amount was quite small; thus the remainder was ordered in English. These books were catalogued and placed in the library for

Programs of assistance . . . should have high aims; . . . and must be adapted to the culture where they are applied . . .

student use. This is quite unique for most libraries in Latin America. In general, libraries are poorly organized and students rarely can use the books since they are under lock and key. The reason for the latter is the ugly phenomena of "caucion" which is a national law administered by the government whereby the person in charge of the library and laboratories is personally financially responsible for all the items in these facilities. If a book is lost or in bad condition, the librarian must pay for the loss or damage. If a piece of laboratory equipment is broken or damaged then the same applies. The result in this system is that the librarian and stockroom keeper rarely let things out of their storage areas.

LABORATORY INSTRUCTIONS

The basic principle behind laboratory work is to reenforce the classroom theory with practical experimentation. Rarely if ever did this exist at Central University on an individual basis prior to 1963. The normal operating procedure was for the professor to do the experiment in front of the class or to have a large group of students attempt the experiment which resulted in one or two doing the actual work. The "caucion" system was one thing to hinder individual work because of lack of equipment. When individual work was initiated at the University, the students progressed rapidly because for the first time they were given the responsibility of items of equipment. They learned to respect the equipment and treat it as their own. With the enaction of the individual laboratory early in the student's academic career it is believed that this gap will be eliminated.

CONCLUSION

Programs of assistance to Latin American Universities should have high aims but should realize that it takes time to achieve these aims. Programs must be adapted to the culture where they are to be applied. Imposing standards of the developed nations on the developing is all wrong. Curriculum changes were enacted in Chemical Engineering at Central University keeping this premise in mind. Student class hours

(Continued on page 152)

SCALING INITIAL AND BOUNDARY VALUE PROBLEMS as a Teaching Tool for a Course in Transport Phenomena

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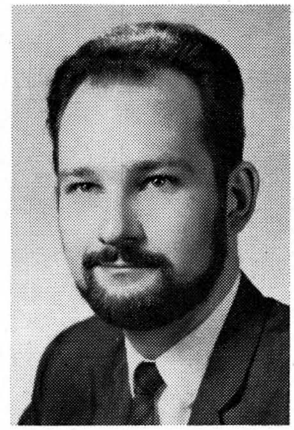

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IN THE COURSE of my chemical engineering studies, one point of continual confusion to me was the manner in which we simplify the exact equations describing a process so that they are amenable to an analytical or numerical solution. For example, in many flow problems we can assume that the flow is fully developed. If I had any doubt as to whether this was a valid assumption I would consult some reference book to find what the entrance length was for the particular flow in question. However, it was not long before I faced the problem of determining the validity of the fully developed flow assumption for flow geometries for which the entrance lengths were not determined; for example, countercurrent gas-liquid film flow in a duct. At this point I was faced with the formidable task of solving the boundary layer equations for the entry region flow.

Consider another example: we all have some feel for the fact that flow through a duct can be considered to be a two-dimensional flow if the aspect ratio (height/width) is small. But, then the question arises, "how small is small?" Again, for many conventional flows we can find the answer to this question in standard references. However, "how small is small" for countercurrent gas-liquid, or liquid-liquid flow in a duct?

Time usually does not permit us to solve the entry region flow problem or the three-dimensional flow problem in order to ascertain the validity of the fully developed flow, or two-dimensional flow assumptions. If the solutions to these flows were trivial we would not be trying to justify simplifying assumptions for the full equations describing them.

It is at this point that the more experienced engineer attempts to invoke some physical insight into the problem in order to have some reasonable certainty that the assumptions he proposes to make are valid. He probably will scale the full equations describing the flow and seek some criteria for discarding terms which will simplify the system of equations to those describing fully developed flow or two-dimensional flow.

Although the practicing engineer is continually faced with justifying the simplifying assumptions he invokes to solve the system of equations describing some process of concern to him, the conventional chemical engineering curriculum has given him little or no practice in doing this with any certainty. Even some of our widely accepted and highly acclaimed texts such as "Transport Phenomena," by Bird, Stewart and Lightfoot[1] are quite prone to say "neglect axial diffusion," "neglect viscous heating effects," etc. The chemical engineering graduate has had little experience in determining when such assumptions can be invoked in practice.

A systematic method of scaling a problem to determine when a simplified set of equations may describe a process has been described in an article by Hellums and Churchill.[2] However their article is mainly concerned with using this method to determine similarity variables for partial differential equations. Although these authors mention the applicability of their method to achieve "minimum parametric representation" of a problem, they offer no examples to illustrate the method for this purpose.

In an attempt to use this method as a teaching tool in my first year graduate course in transport phenomena, I have developed several example problems illustrating the utility of this method for obtaining the minimum parametric representation of a problem. Once having the minimum representation, it is easy to ascertain under what conditions the set of equations will simplify to a form more amendable to solution.

IN PRESENTING this material to my class, I first attempt to apply it to problems for which the students have a good physical feel. A typical example here might be the highly viscous flow (lubrication flow) between two slightly inclined flat plates. The student immediately realizes that many of the assumptions we make for flow between two parallel flat plates can probably be invoked for this flow problem as well. However, he is not quite certain of how much relative inclination of the plates he can tolerate or how high the Reynolds number can be, before these simplifying assumptions begin to become questionable. I use a systematic approach to scaling the equations to give him a firm feel for the assumptions he proposes to make.

After a few problems such as this, I present an example for which the student's physical intuition is somewhat shakey. A typical example here might be judging when convective heat transfer can be neglected in heat transfer with accompanying viscous heating in fully developed laminar slit flow. A few examples such as these, convince most students that the method has real utility in practice.

In what follows, I consider four example problems which I have developed for my transport phenomena course, which illustrate the application of scaling differential equations to obtain the minimum parametric representation. The first two problems are ones for which the student has some physical intuition, namely: 1) when can the lubrication flow assumptions be made for flow between two slightly inclined flat plates, and 2) when can the boundary layer assumptions be made for flow over a flat plate. The last two problems are ones for which he has relatively poor physical insight, namely: 3) when can convective heat transfer be neglected in heat transfer with accompanying viscous heating in fully developed laminar slit flow, and 4) when can penetration theory type arguments be made for film flow down a wall with a soluble constituent.

The first example will be discussed in detail to illustrate the method, whereas the remaining examples merely will be outlined to indicate their applicability to a transport phenomena course, and to illustrate a few of the more subtle concepts involved in scaling.

1. Highly Viscous or Lubrication Flow:

CONSIDER THE VISCOUS flow between two infinite flat plates shown in Figure 1. At the point defined by r = 0, x = 0, a semi-infinite thin baffle is inclined at an angle θ to the centerline. We wish to predict the drag on the baffle and therefore need to derive an expres-

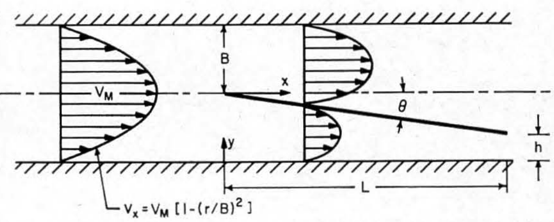

Figure 1. — Lubrication flow over a baffle inserted between two infinite parallel flat plates.

sion for the velocity profile in the baffled region ($0 \leq x \leq L$). Our physical intuition tells us that if the baffle is short (i.e., L is small) we have an undeveloped flow. On the other hand, if the baffle is very long and the Reynolds number very small, the flow locally (at a given x) may be similar to flow between two infinite parallel flat plates. In this latter case, we might suspect that the simplified equations of motion would be identical to those for fully developed flow between two infinite parallel flat plates. Only the boundary conditions would be altered. Despite our good intuition in the problem we do not know "how long is long" or "how small is small." Scaling the complete, two-dimensional equations of motion will enable us to ascertain the validity of our assumptions.

The two-dimensional equations of motion in rectangular coordinates are as follows:

$$\rho v_y \frac{\delta v_x}{\delta y} + \rho v_x \frac{\delta v_x}{\delta x} = -\frac{\delta P}{\delta x} + \mu \left[\frac{\delta^2 v_x}{\delta y^2} + \frac{\delta^2 v_x}{\delta x^2} \right] \quad (1)$$

$$\rho v_y \frac{\delta v_y}{\delta y} + \rho v_x \frac{\delta v_y}{\delta x} = -\frac{\delta P}{\delta y} + \mu \left[\frac{\delta^2 v_y}{\delta y^2} + \frac{\delta^2 v_y}{\delta x^2} \right] \quad (2)$$

$$\frac{\delta v_y}{\delta y} + \frac{\delta v_x}{\delta x} = 0 \quad (3)$$

The appropriate boundary conditions for the flow on the underside of the baffle are:

$$v_x = 0, \; v_y = 0 \text{ at } y = 0 \quad (4)$$

$$v_x = 0, \; v_y = 0 \text{ at } y = B - \left(\frac{B-h}{L}\right)x, \quad 0 \leqq x \leqq L \quad (5)$$

$$v_x = V_m\,[1 - (1 - y/B)^2],\ v_y = 0 \text{ at } x = 0 \tag{6}$$

$$v_x = v_x(y),\ v_y = v_y(y) \text{ at } x = L \tag{7}$$

Boundary conditions 4 and 5 are just the no-slip conditions at the solid boundaries. Boundary condition 6 assumes fully developed slit flow at the entrance to the baffled section. Boundary condition 7 just states that to integrate these differential equations we need to know the velocity profiles at some other value of x, say $x = L$ in this case. The fact that we really do not know these velocity profiles has no bearing on the problem.

We now introduce dimensionless variables involving the unknown scale factors V_o, W_o, P_o, y_o, and x_o:

$$v_y^* = \frac{v_y}{V_o};\ v_x^* = \frac{v_y}{W_o};\ P^* = \frac{P}{P_o};\ y^* = \frac{y}{y_o};\ x^* = \frac{x}{x_o} \tag{8}$$

These dimensionless variables are introduced into equations 1 - 3 and the coefficient of one term arbitrarily is made unity by multiplying through by the reciprocal of its dimensional coefficient. The resulting set of dimensionless equations is given by:

$$\frac{\rho V_o y_o}{\mu} v_y^* \frac{\delta v_x^*}{\delta y^*} + \frac{\rho W_o y_o^2}{\mu x_o} v_x^* \frac{\delta v_x^*}{\delta x^*} = -\frac{P_o y_o^2}{\mu W_o x_o} \frac{\delta P^*}{\delta x^*} + \frac{\delta^2 v_x^*}{\delta y^{*2}} + \frac{y_o^2}{x_o^2} \frac{\delta^2 v_x^*}{\delta x^{*2}} \tag{9}$$

$$v_y^* \frac{\delta v_y^*}{\delta y^*} + \frac{W_o y_o}{V_o x_o} v_x^* \frac{\delta v_y^*}{\delta x^*} = -\frac{P_o}{\rho V_o^2} \frac{\delta P^*}{\delta y^*} + \frac{\mu}{\rho V_o y_o} \frac{\delta^2 v_y^*}{\delta y^{*2}} + \frac{\mu y_o}{\rho V_o x_o^2} \frac{\delta^2 v_y^*}{\delta x^{*2}} \tag{10}$$

$$\frac{\delta v_y^*}{\delta y^*} + \frac{W_o y_o}{V_o x_o} \frac{\delta v_x^*}{\delta x^*} = 0 \tag{11}$$

The dimensionless boundary conditions are:

$$v_x^* = 0;\ v_y^* = 0 \text{ at } y^* = 0 \tag{12}$$

$$v_x^* = 0;\ v_y^* = 0 \text{ at } y^* = \frac{B}{y_o} - \left(\frac{B-h}{L}\right)\frac{x_o}{y_o} x^*;\ 0 \le x^* \le \frac{L}{x_o} \tag{13}$$

$$v_x^* = \frac{V_m}{W_o}\,[1 - (1 - \frac{y_o}{B} y^*)^2];\ v_y^* = 0 \text{ at } x^* = 0 \tag{14}$$

$$v_x^* = v_x^*(y^*);\ v_y^* = v_y^*(y^*) \text{ at } x^* = \frac{L}{x_o} \tag{15}$$

Nondimensionalizing the equations has introduced five arbitrary scale factors given by equations 8. These may be considered as five degrees of freedom which we can choose such that the demensionless terms in equations 9 - 15 have the same relative magnitude. The scaling of these terms is dictated by the boundary conditions and the physics of the problem. That is, for example, the boundary conditions give us the length scale over which the dependent variable v_x goes from its minimum value ($v_x = 0$) to its maximum value ($v_x = V_m$).

We therefore begin determining our scale factors by utilizing the dimensionless boundary conditions. Note that the boundary conditions introduce four dimensionless groups: B/y_o, $[(B-h)/L][x_o/y_o]$, V_m/W_o, and L/x_o. We are free to set these groups equal to zero or unity since they involve the arbitrary scale factors, y_o, x_o and W_o. Our only limitations here are that we do not introduce any mathematical contradictions or violate our physical intuition. Therefore, let us arbitrarily say:

$$B/y_o = 1;\ V_m/V_o = 1;\ L/x_o = 1 \tag{16}$$

This implies that $y_o = B$, $V_o = V_m$, and $x_o = L$ in agreement with our physical intuition on the appropriate scale factors. For example, we could not say $L/x_o = 0$, for this would imply that x_o was infinite which disagrees with the fact that the baffle is of finite length, nor could we also say $[(B-h)/L][x_o/y_o] = 1$, for this would introduce a mathematical contradiction.

WE HAVE GAINED all the information we can from the boundary conditions and have determined three of our five scale factors. The remaining two scale factors will be determined by applying our knowledge to the physics of the problem to the equations of motion. We know, for example, that mass must be conserved; hence our continuity equation continues to be valid in its dimensionless form given by equation 11. If our dimensionless derivatives $\delta v_y^*/\delta y^*$ and $\delta v_x^*/\delta x^*$ are to be equal we must demand that:

$$\frac{W_o y_o}{V_o x_o} = \frac{V_m B}{V_o L} = 1 \tag{17}$$

Hence our scale factor for v_y is given by:

$$V_o = \frac{V_m B}{L} \tag{18}$$

This result was not obvious and we naively might have assumed $V_o = V_m$ had we not scaled the continuity equation properly.

In order to determine our remaining scale factor P_o, we must consider the physical situation for which we are scaling the flow, namely, high viscous flow. This implies that the pressure forces are balanced by the viscous forces rather than the inertia forces. Hence, if our dimensionless pressure gradient in equation 8 is to be of the same order of magnitude as the dimensionless viscous term $\delta^2 v_x^*/\delta y^{*2}$ (The reason for "arbitrarily" making the coefficient of this term unity is now obvious!) we must have

$$\frac{P_o y_o^2}{\mu W_o x_o} = \frac{P_o B^2}{\mu V_m L} = 1 \tag{19}$$

This implies that: $P_o = (\frac{\mu V_m}{B})(\frac{L}{B})$ (20)

Note that the scale factor on pressure is just a measure of viscous shear multiplied by an aspect ratio. This again agrees with our physical intuition for a highly viscous flow, but certainly is not obvious. We naively might have assumed $P_o = \rho V_m^2$ which is the scale factor appropriate to a nonviscous flow.

Introducing the known scale factors into our dimensionless equations of motion yields:

$$\mathrm{Re}\left(\frac{B}{L}\right) v_y^* \frac{\delta v_x^*}{\delta y^*} + \mathrm{Re}\left(\frac{B}{L}\right) v_x^* \frac{\delta v_x^*}{\delta x^*} = -\frac{\delta P^*}{\delta x^*} + \frac{\delta^2 v_x^*}{\delta y^{*2}} + \left(\frac{B}{L}\right)^2 \frac{\delta^2 v_x^*}{\delta x^{*2}} \tag{21}$$

$$v_y^* \frac{\delta v_y^*}{\delta y^*} + v_x^* \frac{\delta v_y^*}{\delta x^*} = -\frac{1}{\mathrm{Re}}\left(\frac{L}{B}\right)^3 \frac{\delta P^*}{\delta y^*} + \frac{1}{\mathrm{Re}}\left(\frac{L}{B}\right) \frac{\delta^2 v_y^*}{\delta y^{*2}} + \frac{1}{\mathrm{Re}}\left(\frac{B}{L}\right) \frac{\delta^2 v_y^*}{\delta y^{*2}} \tag{22}$$

where the Reynolds number is defined by:

$$Re \equiv \frac{B\rho V_m}{\mu} \tag{23}$$

Equations 21 and 22 represent the minimum parametric representation of the problem under the conditions being considered. For limiting values of the two parameters Re and B/L the equations can be greatly simplified. If, for example:

$$\left(\frac{B}{L}\right)^2 \ll 1 \quad \text{and} \quad Re\left(\frac{B}{L}\right) \ll 1 \tag{24}$$

the equations reduce to

$$\frac{d^2 v_x^*}{dy^{*2}} = \frac{dP^*}{dx^*} = \text{a constant} \tag{25}$$

$$\frac{\delta P^*}{\delta y^*} \cong 0 \tag{26}$$

with the boundary conditions

$$v_x^* = 0 \text{ at } y^* = 0 \tag{27}$$

$$v_x^* = 0 \text{ at } y^* = 1 - \left(1 - \frac{h}{B}\right)x^*, \quad 0 \leqq x^* \leqq 1 \tag{28}$$

We were able to make these simplifications under the conditions given by equation 24 because our dimensionless terms have been scaled such that they have the correct relative magnitude dictated by the boundary conditions and the physics of the problem.

The approximate physical conditions under which the above simplified equations can be applied, can be determined from equations 24. We can say, for example, that:

$$\left(\frac{B}{L}\right)^2 \cong 0.1 \text{ and } Re\left(\frac{B}{L}\right) \cong 0.1 \tag{29}$$

thus assuring that the terms these parameters multiply will be at least an order of magnitude smaller than the terms we have retained in equations 21 and 22. These conditions then imply that:

$$\frac{B}{L} \cong 0.32 \text{ and } Re \cong 0.32 \tag{30}$$

Physically these conditions say that the flow must be highly viscous to insure that it can adjust rapidly to the local infinite flat plate flow solution indicated by the solution of equation 25. The aspect ratio B/L must be small to assume that the entrance effects represent an insignificant portion of the total flow regime.

2. Boundary Layer Flow Over a Flat Plate:

THE CONVENTIONAL WAY of arriving at the approriate form of the boundary layer equations is to either pull the appropriate scale factors such as the boundary layer thickness "out of thin air," or to make "hand-waving" arguments for their validity based on the results of the exact solution for the impulsively oscillated flat plate in a quiescent fluid. The boundary layer concept can be rendered far less obscure if we attempt to arrive at the form of the boundary layer equations by scaling the complete two-dimensional equations of motion.

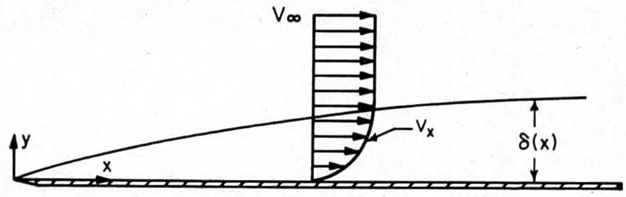

Figure 2. — Boundary layer flow over a flat plate.

The complete two-dimensional equations of motion describing the flow over the flat plate shown in Figure 2 are given by:

$$\rho v_x \frac{\delta v_x}{\delta x} + \rho v_y \frac{\delta v_x}{\delta y} = -\frac{\delta P}{\delta x} + \mu\left(\frac{\delta^2 v_x}{\delta x^2} + \frac{\delta^2 v_x}{\delta y^2}\right) \tag{31}$$

$$\rho v_x \frac{\delta v_y}{\delta x} + \rho v_y \frac{\delta v_y}{\delta y} = -\frac{\delta P}{\delta y} + \mu\left(\frac{\delta^2 v_y}{\delta x^2} + \frac{\delta^2 v_y}{\delta y^2}\right) \tag{32}$$

$$\frac{\delta v_x}{\delta x} + \frac{\delta v_y}{\delta y} = 0 \tag{33}$$

The appropriate boundary conditions are:

$$v_x = V_\infty, \quad v_y = 0 \text{ at } x = 0 \tag{34}$$

$$v_x = v_x(y), \quad v_y = v_y(y) \text{ at } x = L \tag{35}$$

$$v_x = 0, \quad v_y = 0 \text{ at } y = 0 \tag{36}$$

$$v_x = V_\infty, \quad v_y = 0 \text{ at } y = \delta(x), \quad 0 \leqq x \leqq L \tag{37}$$

This example illustrates two concepts in scaling which were not involved in the first example. First, we note that this is a problem for which we are asking whether there is a region of influence wherein viscous forces can be confined, namely the boundary layer. This region of influence, defined by the boundary layer thickness δ, must be introduced into the problem via the boundary conditions, such as was done in Equation 37. Second, the example involves the concept of local scaling. This implies that the equations are scaled at a local x, distinguished by x = L, which may be treated as a constant in the transformation of variables.

Introduce the dimensionless variables:

$$v_x^* = \frac{v_y}{W_o}; \; v_y^* = \frac{v_y}{V_o}; \; x^* = \frac{x}{x_o}; \; y^* = \frac{y}{y_o}; \; P^* = \frac{P}{P_o} \tag{38}$$

The dimensionless groups arising in the boundary conditions and continuity equation enable us to conclude that:

$$x_o = L; \; y_o = \delta; \; W_o = V_\infty; \; V_o = \frac{V_\infty \delta}{L} \tag{39}$$

The fact that boundary layer flows are those in which the pressure forces are of the same order of magnitude as the inertia forces enables us to conclude that:

$$P_o = \rho V_\infty^2 \tag{40}$$

The resulting dimensionless form of the equations of motion is given by:

$$v_x^* \frac{\delta v_x^*}{\delta x^*} + v_y^* \frac{\delta v_x^*}{\delta y^*} = - \frac{\delta P^*}{\delta x^*} + \frac{1}{Re_\delta} (\frac{\delta}{L}) \frac{\delta^2 v_x^*}{\delta x^{*2}} + \frac{1}{Re_\delta} (\frac{L}{\delta}) \frac{\delta^2 v_x^*}{\delta y^{*2}} \tag{41}$$

$$v_x^* \frac{\delta v_y^*}{\delta x^*} + v_y^* \frac{\delta v_y^*}{\delta y^*} = - (\frac{L}{\delta})^2 \frac{\delta P^*}{\delta y^*} + \frac{1}{Re_\delta} (\frac{\delta}{L}) \frac{\delta^2 v_y^*}{\delta x^{*2}} + \frac{1}{Re_\delta} (\frac{L}{\delta}) \frac{\delta^2 v_y^*}{\delta y^{*2}} \tag{42}$$

where the local Reynolds number is defined by:

$$Re_\delta \equiv \frac{\rho V_\infty \delta}{\mu} \tag{43}$$

The fact that viscous forces must be at least as important as inertia and pressure forces in the boundary layer if we are to satisfy the no-slip conditions at the wall, enables us to conclude that:

$$\frac{1}{Re_\delta} (\frac{L}{\delta}) \cong 1 \tag{44}$$

This implies that the boundary layer thickness is given by:

$$\delta \cong \left(\frac{L \mu}{\rho V_\infty}\right)^{1/2} = \left(\frac{L^2}{Re_L}\right)^{1/2} \tag{45}$$

Hence, we have arrived at the correct functional form for the boundary layer thickness if we identify L as the local axial coordinate.

We see from equation 44 that:

$$\frac{\delta}{L} = O\left(\frac{1}{Re_\delta}\right) \tag{46}$$

Therefore, if $Re_\delta \cong 10$ we might expect the following simplified boundary layer equation to apply:

$$v_x^* \frac{\delta v_x^*}{\delta x^*} + v_y^* \frac{\delta v_x^*}{\delta y^*} = \frac{\delta^2 v_x^*}{\delta y^{*2}} \tag{47}$$

$$\frac{\delta P^*}{\delta y^*} = 0 \tag{48}$$

Note the $Re_\delta \cong 10$ implies that $Re_L = \rho V_\infty L / \mu \cong 100$ for the boundary layer analysis to apply. This is in agreement with the analysis of Janssen[3] who showed that the error in the drag coefficient would be approximately 40% at a Reynolds number of 100 and negligible at a Reynolds number of 1000.

The boundary layer equations can be simplified further by rescaling the dimensional form of equation 47, the continuity equation, and the appropriate boundary conditions. However, scaling these equations is a vastly different problem from scaling the full two-dimensional equations of motion which led to these simplified boundary layer equations. The former is a class of problem for which it is not possible to determine the scale factors for all of the independent variables as is done in the problems discussed here. In such cases a similarity variable is suggested. The method for treating such problems is discussed in the article by Hellums and Churchill.[2]

3. Viscous Heating in Laminar Slit Flow:

In THIS CASE we wish to find the conditions under which axial conduction and convection of heat can be neglected relative to radial conduction and viscous generation of heat for the fully developed laminar slit flow shown in Figure 3. If we assume that there is no coupling between the momentum and energy equations, the latter is given by:

$$\rho C_v V_m [1 - (y/B)^2] \frac{\delta T}{\delta x} = k \frac{\delta^2 T}{\delta x^2} + k \frac{\delta^2 T}{\delta y^2} + \frac{4 \mu V_m^2}{B^4} y^2 \tag{49}$$

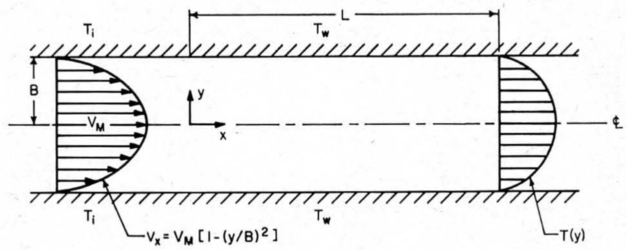

Figure 3. — Viscous heating in laminar slit flow.

The appropriate boundary conditions are:

$$T = T_i \quad \text{at } x = 0 \tag{50}$$

$$T = T(y) \quad \text{at } y = L \tag{51}$$

$$T = T_w \quad \text{at } y = \pm B, \; 0 \leqq x \leqq L \tag{52}$$

$$\frac{\delta T}{\delta y} = 0 \quad \text{at } y = 0 \tag{53}$$

Introduce the following dimensionless variables:

$$T^* = \frac{T - T_r}{T_o}; \; y^* = \frac{y}{y_o}; \; x^* = \frac{x}{x_o} \tag{54}$$

The reference temperature T_r is included as an arbitrary constant in order to make one of the boundary conditions homogeneous. The boundary conditions indicate the following choices for our reference temperature and scale factors:

$$T_r = T_i; \; T_s = T_w - T_i; \; y_o = B; \; x_o = L \tag{55}$$

The resulting dimensionless form of the energy equation is given by:

$$\frac{\rho C_v V_m B^2}{kL} \left[1 - y^{*2}\right] \frac{\delta T^*}{\delta x^*} = \frac{B^2}{L^2} \frac{\delta^2 T^*}{\delta x^{*2}} + \frac{\delta^2 T^*}{\delta y^{*2}} + \frac{4 \mu V_m^2}{k(T_w - T_i)} y^{*2} \tag{56}$$

The criteria for neglecting axial convection and conduction are seen to be:

$$\frac{\rho C_v V_m B^2}{kL} = \mathrm{PrRe}\left(\frac{B}{L}\right) = \mathrm{Pe}\left(\frac{B}{L}\right) \ll 1 \quad (57)$$

and

$$\left(\frac{B}{L}\right)^2 \ll 1 \quad (58)$$

where the Prandtl number and Peclet number are defined by:

$$\mathrm{Pr} \equiv \frac{C_v \mu}{k} \quad (59)$$

$$\mathrm{Pe} \equiv \frac{BV_m \rho C_v}{k} \quad (60)$$

Under these conditions the simplified energy equation yields the solution given by Bird, et. al., in "Transport Phenomena," page 345.[1]

This example illustrates the connection between the lubrication flow assumption (small Re) and the small Peclet number assumption made in heat transfer problems. Scaling the complete equations describing a transport process provides the link between somewhat analogous assumptions. This connection is not nearly so apparent when a less systematic approach is used to arrive at the simplified equations describing the process.

4. Solid Dissolution into a Falling Film:

THE PENETRATION THEORY concept in mass transfer is as obscure as the boundary layer assumption in momentum transfer. We will scale the convective diffusion equation in a manner similar to that used in the developing the boundary layer equations, for the case of solid dissolution into the falling laminar film shown in Figure 4.

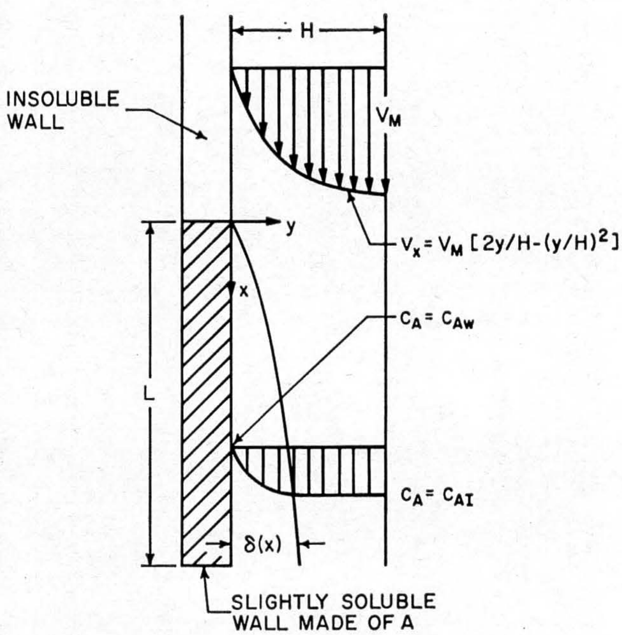

Figure 4. — Solid dissolution into a falling film.

The complete convective diffusion equation for this case is given by:

$$V_m\left[\frac{2y}{H} - \left(\frac{y}{H}\right)^2\right]\frac{\delta c_A}{\delta x} = D_{AB}\frac{\delta^2 c_A}{\delta y^2} + D_{AB}\frac{\delta^2 c_A}{\delta x^2} \quad (61)$$

and the appropriate boundary conditions are:

$$V_m\left[\frac{2y}{H} - \left(\frac{y}{H}\right)^2\right]\frac{\delta c_A}{\delta x} = D_{AB}\frac{\delta^2 c_A}{\delta y^2} + D_{AB}\frac{\delta^2 c_A}{\delta x^2} \quad (61)$$

$$c_A = c_{Ai} \text{ at } x = 0 \quad (62)$$

$$c_A = c_A(y) \text{ at } x = L \quad (63)$$

$$c_A = c_{Aw} \text{ at } y = 0,\ 0 \leq x \leq L \quad (64)$$

$$c_A = c_{Ai} \text{ at } y = \delta_c(x) \quad (65)$$

Introduce the following dimensionless variables containing the arbitrary parameters c_r, c_o, y_o, and x_o.

$$c_A^* = \frac{c_A - c_r}{c_o};\quad y^* = \frac{y}{y_o};\quad x^* = \frac{x}{x_o} \quad (66)$$

The boundary conditions indicate the following choices for the arbitrary parameters:

$$c_r = c_{Ai};\ c_o = c_{Aw} - c_{Ai};\ y_o = \delta_c;\ x_o = L \quad (67)$$

The dimensionless convective diffusion equation then assumes the form:

$$\left[\left(\frac{2\delta_c}{H}\right)y^* - \left(\frac{\delta_c}{H}\right)y^{*2}\right]\frac{V_m \delta_c^2}{D_{AB}L}\frac{\delta c^*}{\delta x^*} = \frac{\delta^2 c^*}{\delta y^{*2}} + \left(\frac{\delta_c}{L}\right)^2\frac{\delta^2 c^*}{\delta x^{*2}} \quad (68)$$

Since the convection term must be of the same order of magnitude as the cross-stream diffusion term if we are to satisfy the boundary conditions at the wall, we must have:

$$\frac{V_m \delta_c^2}{D_{AB}L} \cong 1 \quad (69)$$

This implies that:

$$\delta_c \cong \left(\frac{D_{AB}L}{V_m}\right)^{1/2} = \left(\frac{HL}{\mathrm{Re\ Sc}}\right)^{1/2} = \left(\frac{HL}{\mathrm{Pe}}\right)^{1/2} \quad (70)$$

In order for the penetration theory equations to apply we must have

$$\left(\frac{\delta_c}{L}\right)^2 \ll 1 \quad (71)$$

and

$$\left(\frac{\delta_c}{H}\right)^2 \ll 1 \quad (72)$$

where H is the film thickness. This implies that:

$$\frac{D_{AB}L}{V_m H^2} = \left(\frac{1}{Re\ Sc}\right)\left(\frac{L}{H}\right) = \left(\frac{1}{Pe}\right)\left(\frac{L}{H}\right) \ll 1 \qquad (73)$$

Hence we see that the ratio of the contact time to the characteristic diffusion time must be small if the penetration theory analysis is to apply. Most transport phenomena texts state that merely the contact time must be small. Scaling the equations tells us that the relative contact time is the important parameter which must be considered to ascertain the validity of the penetration theory assumption. Note that equation 73 implies that the penetration theory arguments will ultimately break down at large L, (x).

The simplified dimensional equation that describes the mass transfer under penetration theory arguments is thus:

$$\frac{2V_m y}{H} \frac{\delta c_A}{\delta x} = D_{AB} \frac{\delta^2 c_A}{\delta y^2} \qquad (74)$$

The simplified boundary conditions are:

$$c_A = c_{Ai} \quad \text{at } x = 0 \qquad (75)$$

$$c_A = c_{Aw} \quad \text{at } y = 0,\ 0 \leqq x \leqq L \qquad (76)$$

$$c_A = c_{Ai} \quad \text{at } y = \infty \qquad (77)$$

The last boundary condition follows from the fact that δ_c is so small that for all practical purposes the boundary condition at the gas-liquid interface can be considered to be at infinity. The solution to this simplified problem is outlined on page 551 in "Transport Phenomena," by Bird et. al.[1]

This example illustrates the connection between the boundary layer assumption (large Re) made in momentum transfer and the penetration theory assumption (large Pe) made in mass transfer.

SUMMARY

A systematic approach to scaling the mathematical description of transport phenomena can be summarized as follows:

1. Write the complete differential equations and boundary conditions describing the process. In problems involving a "region of influence" such as boundary layer problems, the bound on the region such as the boundary layer thickness must be introduced in the boundary conditions.

2. Form dimensionless variables by introducing arbitrary scale factors on all dependent and independent variables. Arbitrary reference factors may be introduced to make certain boundary conditions homogeneous.

3. Introduce these dimensionless variables into the differential equations and their boundary conditions.

4. Arbitrarily make the coefficient of one term in each differential equation and boundary condition unity by dividing through by its dimensional coefficient.

5. Attempt to determine the arbitrary scale factors and reference factors by setting appropriate dimensionless groups equal to zero or unity. Which groups are chosen in this step depends on the physical conditions for which the equations are being scaled. Characteristic lengths can usually be determined from the dimensionless groups generated by the boundary conditions. However, characteristic times, velocities, etc., more frequently are determined from dimensionless groups generated by the differential equations. The guideline in determining the unknown scale and reference factors is to avoid introducing any mathematical contradictions and to not violate one's physical intuition.

6. In problems for which all the scale and reference factors can be determined in this manner, the resulting dimensionless form of the differential equations and boundary conditions is the minimum parametric representation of the problem. Problems for which not all the scale factors on the independent variables can be determined in this manner suggest a similarity solution.

7. The minimum parametric representation of the problem can be used to ascertain under what approximate conditions the mathematical description of the problem can be simplified to yield a more feasible analytical or numerical solution. It also suggests the appropriate parameters for a perturbation or a symptotic solution for the complete mathematical description of the problem.

The systematic approach to scaling the mathematical description of transport phenomena is an effective teaching tool for a transport phenomena course. It provides a means by which the validity of various simplifying assumptions introduced in the mathematical description of transport phenomena can be quantitatively ascertained. It also can be used to illustrate the analogy between the assumptions made in simplifying heat, mass, and momentum transfer problems respectively.

NOMENCLATURE

B	half width of slit
c_A	concentration of component A
C_v	heat capacity at constant volume
D_{AB}	diffusivity of component A in B
h	height of baffle at $x = L$
H	film thickness
k	thermal conductivity
L	axial length
P	pressure
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number
Sc	Schmidt number
T	temperature
V_m	maximum velocity
v_x	axial velocity
v_y	transverse velocity
V_∞	approach velocity
x	axial coordinate
y	transverse coordinate

δ	momentum boundary layer thickness
δ_c	concentration boundary layer thickness
θ	angle of inclination of baffle
μ	viscosity
ρ	density

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KLINZING: ECUADOR (Continued from page 146)

were reduced from 40 or 50 per week to 25 or 30 per week. The complicated thesis regulations were modified to a more efficient system. Scholarship programs for students and professors to improve their knowledge and return to their Universities seem to be the salvation for many Latin American Universities. Responsibility needs to be fostered in the students in Latin American Universities. This cannot be accomplished unless they are given the opportunity to practice it in and out of the classroom. In Engineering assistance programs the work is much easier than in other areas such as History, Administration, Education, etc. The reason for this ease is because the amount of physical equipment that can be employed in this type of assistance. People are anxious to change and accept new ideas when they see one of the means of change physically before them. Cooperation was excellent and enthusiasm for improvement notable. The School contains many capable and dynamic professors and administrators. It is believed with this leadership the School will progress at a steady rate. One working in these programs of assistance should be flexible in operation and ideas. He should not concede on ideals. For full effectiveness in such a program a tour of duty should be no more than two years. Speaking the language of the host country is an invaluable asset in the entire endeavor.

(Continued from page 116)

The wild areas of the U.S. have had a bad ten years. Visits to most of the National Parks are rationed. This caused people to flock to adjacent wild areas. The use of motorized bikes, snowmobiles and helicopters has opened even the most remote regions to hordes of people. No species became extinct during the decade but the grizzlies, eagles and condors are very close to it.

Politically the world of 1980 is farther than ever from "one world" but is closer to two worlds. The Vietnamese war was never officially ended. Neither was the Korean war for that matter. The U.S. slowly withdrew its troops during the early 1970's. Control of all of Vietnam slipped into the hands of a government continually more Communist oriented. Red China gained more control over the country with the aim of securing the benefits of the Mekong rice bowl for herself. Then pressure was exerted against Laos and Thailand. These countries asked for U.S. help from the aggressor. The U.S. declined, however, having heard this cry before.

In India and Pakistan, food riots, epidemics and general misery made their national governments almost powerless to guide and control these countries. Red China now virtually controls southeast Asia, but is no better off for it. She inherited more people than food. Her border clashes with Russia always were followed by a pull-back when Russia acted tough. Israel stands at the same borders she had at the end of the 1967 war. The Arab nations of Egypt and Syria are overflowing with starving people, having increased by 12 million in the past decade. They are much too weak to pose a military threat to Israel and Russia apparently decided back in 1972 that nothing was to be gained by continually arming the Arabs. Russia appears to be having considerable difficulty just feeding her own population, now 270 million, and doesn't seem to have any food to spare for starving partners. Latin America now exceeds North America in population but in not much else. Most of the countries of Central America and northern South America have had a succession of military coups and "popular" uprisings.

Back in 1970 I thought that homo sapiens was about three generations from extinction. Today, in 1980, I am not quite so pessimistic. Two hopeful signs have emerged. Almost all of the countries of the world have massive educational campaigns advising "Replace Yourself Only." Birth control is available and cheap worldwide. This alone won't do the job since large pockets of resistance to limited families still exist in South and Central America, India and Southeast Asia, and in the Arab countries. The other development is the recently introduced method of pre-selection of the sex of offspring. In the countries where there is the greatest resistance to family limitations, there is also the greatest desire for sons. In India, sons are social security; in Latin America, the measure of a man's "manhood." With these countries in such a chaotic condition, statistics are difficult to obtain but there is evidence that a great preponderance of male births is beginning to occur. It will take another 15 to 20 years until we know whether this creates more problems than it solves and also whether the world population is actually starting to decline as some observers claim.

Lloyd Berg, Montana State University

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