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The International Organization for Standardization has assigned the code US ISSN 0009-2479 for the identification of this periodical.
ACKNOWLEDGMENTS

Industrial Sponsors: The following companies donated funds for the support of CHEMICAL ENGINEERING EDUCATION during 1975-76:

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ON GILL'S ULTIMATE REPORT—NOI SPERIAMO

Sir:

Quite recently Provost Gill of SUNY Buffalo has visited upon us an evaluation of graduate Chemical Engineering efforts, in the spirit (indeed in carbon copy) of the celebrated Cartter report et seq. That the “Gill Report” has provoked comment, I have no doubt. That the “Gill Report” has done justice to Minnesota, I have no doubt whatsoever. They are “uno numero.” But that, fair reader, ends equity. Witness the “top 20.” Look into your minds, I plead. Permit me a few undemocratic observations.

As I am a professor at Notre Dame, I comment not upon our statistically established status in the Gill report. In fact, for reasons set forth below, we could not care less, save for the obvious acknowledgment that the University of Minnesota is rightfully ranked No. 1 and several other quite distinguished departments hold an elevated status.

But what is the nature of that properly first ranked department? It is, pardon me, catholic in instinct and implementation. The other 19 of the top 20? To be sure, in catalysis and fluid mechanics, Stanford is pre-eminent. In the several areas of chemical engineering science, surely Delaware emerges. One can go on, citing specific areas of expertise and assigning particular departments the role of “uno numero.” My point, which I trust is virtually obvious, is that the ranking of graduate departments of chemical engineering must respect particular areas which, though ignored in the past of the unit operations mentality, now yield to delineations and specializations heretofore unanticipated. Which is to say, how do we rank a chemical engineering department of strength in, say, surface catalysis (e.g., Stanford) with one of signal merit in, say, thermodynamics (e.g., Florida or Oklahoma)? Tis the problem, dear reader, of contrasting oranges and apples.

Permit me a further illustration: VPI boasts a rather strong chemical engineering group (in my opinion) in the area of fundamentals of food sciences, including that most glorious of inclinations—wine technology. Delaware, a department of admirable scope and depth, claims not such expertise. How does the Gill report rank these departments? See for yourself. MIT boasts of a just reputation insofar as they and Michigan virtually invented “our trade,” at a time when Minnesota could claim naught but Bronko N. No informed citizen of our chemical engineering group would or could place MIT and/or Michigan in the same province of universal excellence as is now occupied by Minnesota. Indeed, I, quite frankly, am very, very, suspicious of a goodly number of rankings, ala Gill, which place greats and near-do-wells within the top 20. Indeed, the top 30 or 40.

Continued on page 152.

Editors Note:
The following response was received from Provost Gill. (For another approach to the rating of departments, see the paper by Griskey in this issue.)

RESPONSE TO J. J. CARBERRY

Sir:

If Professor Carberry (B.S. 1950; M.S. 1951, Notre Dame; Ph.D 1957, Yale) is trying to say that peer evaluations, which disagree with his opinion, are meaningless, I disagree with him completely. It seems that Carberry feels that one man’s opinions are superior to collective peer judgments. However, it has been demonstrated in many studies (i.e., Bernier, et al, Chemical Engineering Education) that collective peer evaluations correlate highly with objective measures of excellence such as numbers of papers published, research expenditures, citations, PhD’s produced, etc.

I’m sorry that the chemical engineering departments are not viewed by other faculty colleagues the way Professor Carberry would like them to be. But I can assure him that no one at Buffalo, including me, participated in any of the rankings, including those of Notre Dame and Yale.

Faculty members at all ranks from 19 schools other than Buffalo provided usable responses. Some schools provided more than one usable response. To my knowledge no bribes of any kind were offered to influence the rankings one way or another.

It is worth noting that the introduction to the report includes the following statement:

“An attempt was made to obtain what seemed to be a reasonable mix of raters among the various academic ranks of assistant, associate, and full professor. However, this study is not purported to be as comprehensive and has not been designed with the care given to the details of statistical design that characterized the two previous American Council on Education studies. Therefore, the results should be viewed in this context. That is, no doubt departments which should have been included have been omitted and the ratings of those departments which have been included certainly are subject to significant, but undetermined, errors.”

State University of New York at Buffalo
William N. Gill
IOWA'S TRADITIONAL commitment to quality education at every level was established in 1868 when Iowa State became the first institution in the U.S. to qualify under the Morrill Act as a land grant college. Since the founding of the Department of Chemical Engineering in 1913, the university and the department have grown together in scope and diversity from primarily agriculturally based institutions into multi-faceted and diverse entities. The College of Engineering now enrolls more than 3000 students annually out of the 21,000 attending the university, and has become one of the largest engineering colleges in the U.S. Under the leadership of several outstanding individuals, the ChE program now occupies an eminent position in the college, enrolling over 250 undergraduate and 50 graduate students annually. The faculty of 18 holds degrees from a total of 25 schools, and the physical facilities available for instruction and research now occupy over 26,000 square feet of space.

Following the graduating of the first class in 1914, the first graduate degrees were offered in 1918, and the first Ph.D. granted in Chemical Engineering in 1925. To Dr. Orland R. Sweeney goes the credit for the development of the department from the 1920's to the 1940's. Dr. Sweeney, who became a true Iowa State legend, had a creative approach to research, and his enthusiastic promotion of the profession was responsible for the rapid development of the department during the 1930's. Sweeney truly believed that the condition of simply being a chemical engineer endowed one with all of the necessary qualities for success. On more than one occasion he would extoll the virtues of a student to a prospective employee and only after finishing the testimony inquire as to the student's name. His partial deafness was used as a weapon by the simple device of turning off his hearing aid at the appropriate moment. He was probably the only ChE department head in the U.S. to make frequent use of a fire pole to make optimal use of his time.

THE SWEENEY ERA

DURING THE SWEENEY era the department developed a worldwide reputation in the areas of the utilization of agricultural by-products, water treatment and ion exchange, filtration technology under Dr. B. F. Ruth, and in fertilizer technology. During this period Iowa State College itself was growing from an agricultural and engineering school into a modern university. Following Sweeney's retirement in 1946, Dr. G. Leon
Bridger, now a department chairman at Georgia Tech, led the department until 1955. His major contribution was to use this experience gained in fertilizer technology at TVA to establish a research program that still continues today. Dr. Morton Smutz, now an associate dean at the University of Florida, was department head from 1955 to 1961. In 1961 Dr. George Burnet became head, and the department entered a period of growth and expansion in faculty size and facilities which was characteristic of much of the university during the past decade. In 1964 the department celebrated its 50th anniversary by moving into Sweeney Hall, a large three-story building which now houses most of the department’s services and facilities. In 1971, Dr. David R. Boylan moved from his position as a faculty member in the department and director of the Engineering Research Institute to become Dean of Engineering. In 1973, administrative reorganization resulted in the department becoming combined with the existing graduate program in Nuclear Engineering. The department now operates with two separate faculties, and Dr. M. A. Larson has been assisting in the administration of the ChE program since the reorganization.

In addition to the facilities available in Sweeney Hall, which include a large number of graduate student research laboratories, a large reading room, shops, classrooms and faculty offices, the department also operates a large unit operation teaching laboratory and a digital control laboratory containing a number of analog and digital computing devices. As a result of a long association with the Ames Laboratory of the U.S. Energy Resource Research and Development Agency (formerly AEC) on campus, there are also additional excellent research facilities available in that area.

The undergraduate program at Iowa State is distinguished in the breadth of educational opportunities that are available to the student. The quality of students entering Iowa State, as measured by any of several national indicators is unusually high. Over one-third of the students entering chemical engineering are from the upper 5% of their graduating high school class. It is not unusual for one-fourth of the average graduating B.S. class to continue into a graduate school. Curriculum design and development has therefore been a continuous challenge, and the present undergraduate curriculum has developed to maintain the department’s traditional strong emphasis in design and also provide a strong base for continuing study in engineering. The traditional sequences in unit operations and transport phenomena were integrated in 1970 into a four quarter sequence. Undergraduate courses in process optimization, digital and analog simulation, chemical reactor design, and an introductory freshman level design experience supplement the traditional sequences. A special feature is the opportunity for advanced undergraduates to designate up to 15 credits to concentrate in a specialized area such as applied mathematics, biochemical or biomedical engineering, polymers, applied chemistry, or energy resource development. A large number of ChE undergraduates participate in the University Honors Program, which allows exceptional students to develop individualized programs which fit their career goals. The department sponsors a 4 day industrial plant inspection trip in the junior year to the St. Louis area. An extensive Cooperative study program with several companies in the chemical industry is available so that students desiring work experience can spread their education over a 5 year period and gain enriching experience.

To Orland R. Sweeney goes the credit for the development of the department from the 1920's to the 1940's. During the Sweeney era the department developed a worldwide reputation in the areas of the utilization of agricultural by-products, water treatment and ion exchange, filtration technology under Dr. B. F. Ruth and in fertilizer technology.

A special opportunity is also available in the Foreign Study Program, in which a group of 10 to 16 advanced students each year have been able to complete up to 12 credits of required work during a 6 week stay at University College in London, England. This program, instituted in 1973, has been very popular, both with students and faculty. Since the course of study takes place in June and July, students can combine a period of traveling in Western Europe following the program. Faculty at University College, in conjunction with an Iowa State facul-
ChE undergraduates participate in many student activities on the campus. One such opportunity is provided by the very active student AICHE chapter, which last year hosted the Great Plains Student Chapter Conference. Also, the local chapter of Omega Chi Epsilon, the national chemical engineering honorary, is active in promoting interchange programs with the faculty, in the form of evening fireside visits and other events.

Generous support from a number of chemical firms has enabled the department to provide a large number of attractive undergraduate scholarships, including a four-year scholarship sponsored by the Dow Chemical Company and awarded annually to the outstanding Iowa high school graduate entering ISU in ChE, and a number of scholarships for women students, sponsored by the Celanese corporation. As in many chemical engineering departments, the number of women undergraduates is steadily increasing.

The 50 graduate students pursuing Master of Science and Doctor of Philosophy degrees at ISU carry out research in a large number of areas. Over 60 ISU alumni are now active as faculty members in universities around the U.S., a fact which attests to the quality and flavor of the graduate program. During the last 15 years, ChE research has become increasingly interdisciplinary, and the work going on at Ames is no exception. Following a long period which saw ISU develop a world-wide reputation in fertilizer technology and in the utilization of agricultural by-products, resulting in well over 40 patents, new research areas have developed in areas such as coal technology under T. D. Wheelock and A. H. Pulsifer; industrial crystallization under M. A. Larson; and biochemical engineering under the direction of P. J. Reilly. Large external contracts have been developed in each of these areas. In addition, research work at the Ames Laboratory in interfacial mass transfer by L. E. Burkhart, heterogeneous catalysis under R. G. Bautista, and liquid metal technology with George Burnet has become well known. Since 1966, the department has been an active collaborator in the Biomedical Engineering Program, with work on heat and mass transfer in applied physiology under R. C. Seagrave. Additional research areas include J. C. Hill's work in fluid mechanics, W. H. Abraham's program in process analysis, Kenneth Jolls' interests in thermodynamics, J.D. Stevens' work in emulsion polymerization, and D. L. Ulrichson's program in thermodynamics and hydrogen as an energy source. A recent addition to the faculty, Dr. Charles Glatz, brings expertise in biological mass transfer.

The curriculum leading to the M.S. and Ph.D. degrees is based on core sequences in transport operations, thermodynamics and reactor design, and applications of mathematics in ChE. In addition, advanced courses in process dynamics, non-equilibrium thermodynamics, biochemical engineering, coal technology, crystallization, heterogeneous catalysis, and applied electronic instrumentation are available for those wishing to specialize. Advanced sequences in transport phenomena and simulation are also available for advanced students.

Graduate students at Iowa State may also participate in interdisciplinary programs in Water Resources, Energy Resources, Technology and Social Change, and Biomedical Engineering. Excellent programs in chemistry, nuclear engineering, computer science, physics, and mechanical engineering are also used as minor areas.

The Engineering Research Institute and the Ames Laboratory have traditionally provided strong assistantship support, and in combination with a healthy grant program from private industry and successful research contract efforts by
Burkhart and Collins doing digital control.

faculty a broad base for graduate support has been assembled.

FACULTY ACTIVITIES

In addition to their teaching and research activities, Iowa State's ChE faculty have been unusually active in the areas of national and international service. A long list of research publications, patents, and textbooks which is characteristic of many outstanding faculties is supplemented by the extramural accomplishments of the group. George Burnet is currently serving as President-elect of ASEE and as chairman of the important Engineering Education and Accrediting Committee of the Engineers Council on Professional Development. Maury Larson is serving as chairman of the Division of Fertilizer and Soil Chemistry of the American Chemical Society. Both George Burnet and John Stevens have recently served terms as national Presidents of Omega Chi Epsilon. Burnet and Larson each spent two month periods as NSF Science Improvement Program consultants at The Indian Institute of Technology in Karagphur, while Bill Abraham spent two years on leave as a Ford Foundation Fellow in Manila, the Philippines, developing a graduate program in ChE there. Allen Pulsifer spent one year at Prairie View A & M college in Texas helping to establish a ChE program while John Stevens spent one year sponsored by AID visiting in the ChE Department at Hacettepe University in Ankara, Turkey. More recently, Larson spent a year in residence at University College in London as the Shell Visiting Professor and conducting crystallization research. He also participated in an exchange program in Czechoslovakia and Poland. Seagrave spent one year at the Institute for Medical Physics in Utrecht, the Netherlands doing research in anesthesiology. Currently, Bautista and Pulsifer are spending one year periods in England and West Germany respectively pursuing research in their areas.

The department has been fortunate in recent years to have had several outstanding visiting professors. This year, Professor Henry Rojkowski from Warsaw is in residence teaching and doing research in crystallization. Other recent visitors have included Dr. Ted White from the University of Queensland in Australia and Dr. Norman Harnby from the University of Bradford in England. Next year Dr. John Garside from the University College of London will be visiting.

The faculty have also been active in consulting work, and in addition have received many honors. George Burnet was named Anson Marston Distinguished Professor of Chemical Engineering in 1975. Professors Larson and Seagrave have both been named recipients of the North Midwest ASEE Outstanding Teacher Award, while John Stevens was named as a winner of the Standard Oil Outstanding teacher award in Engineering.

Compared to the legendary antics of the colorful Dr. Sweeney, our modern faculty activities take on more pastel hues. Like many of our colleagues around the U.S., we have become affected by the physical fitness craze, and on any given noontime several faculty may be observed running, biking, or playing basketball, volleyball, handball or tennis. Perhaps we are distinguished more by the combination and range of our interests, which find us with two licensed pilots (Abraham and Wheelock), two gentlemen farmers (Larson and Collins), a railway station demolition expert (Ulrichson), a professional musician (Jolls), a part-time political hack (Seagrave), and a host of quasi-expert bowlers. Chemical engineering, as Dr. Sweeney would attest, is an exciting profession, and life at Iowa State is no exception.
The Chemical Engineering Department at the Johns Hopkins University didn't fold while James M. Douglas loitered through his undergraduate years at Hopkins. It was intact even while Stan Middleman wandered through Maryland Hall. It collapsed as we joined forces at the University of Massachusetts. It may well have been Douglas who precipitated the debacle; the exodus of students (and faculty) grows as they pass down the corridor, and among others, Jim Douglas finds his way to the Top of the Campus for the beers and Friday afternoon advising session.

For that matter a few years at U. Mass. and the Commonwealth nearly folded. The Hopkins days may well have played a large role in the development of our "enfant terrible." Long hard intense nights at poker sharpened his killer instinct. The warm Baltimore spring may well have brought him to Homewood field to watch Morrill and Webster and others show Maryland's Terrapins how to play lacrosse. These athletic talents became nearly as highly developed as his skill in emptying beer cans. In the latter day academic profession, such skill is essential in maintaining communication with students.

At U. Mass/Amherst, a migration occurs from Goessmann Lab nearly every Friday just after 4:00 p.m. The exodus of students (and faculty) grows as they pass down the corridor and among others, Jim Douglas finds his way to the Top of the Campus for the beers and the Friday afternoon advising session. A university, a school, a department must strive to be a community of scholars. They must meet, they must talk, exchange ideas. These sessions are one way towards those goals. These sessions are of finite duration, however; Betsy and the hills of Leverett do need Jim. Robbie, his son, took to downhill skiing this year and Jim, as accomplished a cross-country skier as he is, still had a transition to make. Changes are not new to the Black Douglas. His career has provided enough for him.

A graduate of the John Hopkins University, he migrated the short distance to Newark, Delaware, in the late 50's and served his time as a graduate student in the vigorous Chemical Engineering Department at the University of Delaware. His companions in crime of the time were Forrest Mixon, Marty Wendel, Steve
Whitaker, Bill Abraham, and many others. The tutelage of Bob Pigford did him no harm, but he regrets to this day the anger which preceded disposal of the classic text by Marshall and Pigford.

I can't see Douglas having changed political views in the last 20 years. His intensity may well have mellowed. Douglas, would you believe, served an Army tour. His stories mirror his perennial frustration with ineptitude and red tape, but more on that later.

**STRONG INDUSTRIAL BACKGROUND**

When John Eldridge began to assemble the personnel to build a strong department of Chemical Engineering, his fundamental premise was to provide a sound undergraduate program through a faculty with substantial industrial experience. Jim Douglas was no exception. His experience with Atlantic Refining flavors his senior design course. Jim's interest in design is in some sense counter-cultural. A large fraction of design teaching in chemical engineering has a focus in computer aided design. Although Douglas is aware and used computer aided design, a significant fraction of his teaching and research effort is directed towards simple design algorithms... in a sense to offer credence to the fabled design engineer who based his designs on years of experience. Such a set of research interests is not at all out of character for Jim. He has managed to attack consistently difficult problems and arrive at simple solutions.

After several years at Atlantic, Jim had an industrial sabbatical at Imperial College (University of London). Contrary to most views, he did use his leave to good purpose. He lived in Wimbledon and did not play tennis. He, Betsy, Lynn, and Robby travelled through Britain, visiting even the Borders of an earlier Douglas. From Jim's work with Dave Rippin (now ETH, Zurich) came periodic operation. He and Rippin showed the marked improvements in performance which can be obtained in chemically reacting systems through forced oscillations. This work opened a new research area for him, work which continues.

It was through the work on periodic operation that Jim began his two-volume text on Process Control and Dynamics. The books began as one volume, but finished as two, the mass of information to be distributed having grown continually. His ideas were tested on students, on colleagues, on himself.

Cooling a cup of coffee may not sound like an exciting chemical engineering problem, but it is not unusual to find students in Jim's heat transfer course measuring the temperature history of a cup of coffee. This problem shows Jim's approach to things... define a problem in the simplest description possible, make some experimental measurements, and refine your model. This pattern of analysis is what has led to Jim's latest research efforts in simple design algorithms.

Douglas' office is at the back of Middleman's laboratory, populated with aspiring rheologists. They were sufficiently distressed by the frequency of the question, "Is Dr. Douglas in?" that they put up a sign with a movable arrow pointing to In, Out, or Maybe. Another sign was soon necessary to identify whether the first was true or false.

One aspect that students see little of are his continuing efforts in the development of a sense of scholarship in his colleagues. He has not always been successful, but he does keep trying and we all will discover soon that he was right all along. His latest frustration came this spring in the senior design course. Plagued with "senioritis," the class was nearly in rebellion over the workload. They expected to coast while Jim expected them to learn.

I suggested earlier that Douglas has little patience with ineptitude and red tape. "Notre enfant Terrible" mustered the forces of the university administration against him in a valiant attempt to expose the usual ineptitude of

Continued on page 145.
HOW TO GET THE MOST OUT OF AN EQUATION WITHOUT REALLY TRYING*

RUTHERFORD ARIS
University of Minnesota
Minneapolis, Minnesota 55455

MAXIMS FOR MATHEMATICAL MODELLING
1. Cast the problem in as elegant a form as possible.
2. Choose a sympathetic notation, but don’t become too attached to it.
3. Make the variables dimensionless, since this is the only way in which their magnitudes take on general significance, but do not lose sight of the quantities which may have to be varied later on in the problem nor forget the physical origin of each part.
4. Use a priori bounds of physical or mathematical origin to keep all variables of the same order of magnitude, letting the dimensionless parameters show the relative size of the several terms.
5. Think geometrically. See when you can reduce the number of variables (even at the expense of first treating an over-simplified problem), but keep in mind the needs of the general case.
6. Use rough and ready methods, but don’t carry them beyond their point of usefulness. (E.g. Isoclines in the phase plane).
7. Find critical points and how the system behaves near them or what is asymptotic behaviour is at long or short times.
8. Check limiting cases and see how they tie in with simpler problems that can be solved explicitly.
9. Use crude approximations, e.g. 1-point collocation. Trade on the analogies they suggest, but remember their limitations.
10. Rearrange the problem. Don’t get fixed ideas on what are the knowns and what the unknowns. Be prepared to work with implicit solutions.
11. Neglect small terms, but distinguish between regular and singular perturbations.
12. Use partial insights and despise them not. (E.g. Descartes’ rule of signs).
13. These maxims will self-destruct. Make your own!

IT IS A COMMON PARADOX that one should only start computing after one knows the answer. Not to be taken to literally, it emphasizes that one should learn as much as possible about a problem before computing any case or sequence of cases so that the output of the computer may be critically appraised, for, without this critical oversight, the computer can produce an output more tedious and turgid than the so-called play-boy philosophy. It is in any case part of the ‘craft and sullen art’ of the engineer or applied scientists to bring his problem into its most responsive formulation and to explore the modes of its solution as delicately as possible before proceeding to its complete analysis. From one point of view it requires sensibilities which are ‘nascitur non fit,’ but from another it is surely an art we may all strive after even if we despair of its mastery.

Of the texts on applied mathematics and engineering analysis the best may perhaps instruct by example, but only Segel and Lin’s recent masterpiece [1] attempts to unfold some of the techniques of right formulation. There the question of reduction to dimensionless form and the scaling of equations is carefully and systematically explained. It will be clear that this essay is influenced by what they have done, both in this regard and in the play they have given to perturbation methods. The maxims of modelling that I have ventured to set down are a preliminary attempt to codify some of the mental processes of the chemical engineer as he probes and explores a problem. Like all maxims they tend to have the unassailable probity of “this ye ought to have done and not to have left the other undone.”

*EDITOR’S NOTE: In this issue, CEE begins a new department: ChE LECTURES. We intend to publish seminars and lectures on important areas of modern chemical engineering. If you feel that one of your seminars or lectures on a certain topic would have pedagogical or tutorial value and would be of general interest to our erudite readers, please send the manuscript to the editor for review. We would appreciate comments from our readers on this new department as well as suggestions for authors of papers.
Dr. Rutherford Aris was born in England in 1929, studied mathematics in the University of Edinburgh and taught it to engineers there. He has degrees from the University of London (B.Sc. (Math); Ph.D. (Math. and Chem. E.); D.Sc.). He worked a total of seven years in industry, but since 1958 he has been in the Chemical Engineering Department at the University of Minnesota enjoying the liveliness of its interests, both technical and cultural, and endeavouring to contribute to this vitality and communicate it to his students.

Nevertheless they should be looked on with a quizzical eye and subjected to a more than usually critical appraisal. They are dignified with numbers merely to invite the participation of the reader by pencilling them in the margin at the stage or stages of the example where they are most obviously invoked.

1. SETTING UP THE EQUATIONS

The example will be the elementary and familiar one of a single nonisothermal reaction in a catalyst pellet of arbitrary shape for, though it might be argued that I am getting the benefit of a good deal of hindsight, its very familiarity will allow us to concentrate on the method rather than be preoccupied with the matter. If the reaction is between the S species \( A_i \) it may be written \( \sum \alpha_i A_i = 0 \) giving a positive sign to the stoichiometric coefficients of those species which are regarded as the products of the process. In the Knudsen diffusion regime the effective diffusion coefficients \( D_{ij} \) may be regarded as independent and mass balances for over an element of volume within the catalyst pellet for each species lead immediately to the S equations

\[
D_{ij} \nabla^2 c_i + \alpha_i \rho_b S \phi f(c_1, c_2, ..., c_S, T) = 0 , \quad (1)
\]

where \( c_i = c_i(r) = \text{concentration of } A_i \),

\( T = \text{temperature} \),

\( \rho_b = \text{bulk density} \),

\( S = \text{catalytic area per gram} \),

\( f = \text{reaction rate per unit catalytic area} \).

The Laplacian is with respect to the position variables \( r = (x, y, z) \) within the pellet which is assumed to have uniform properties. Into the formulation of this equation have gone the principle of the conversation of matter and two constitutive relations. One is a generalization of Fick’s law which asserts that despite the physical complexity of the porous medium the flux can be related to the concentration gradient by an effective diffusion coefficient. The other is the kinetic law that may be embodied within the rate expression \( f \). With the validity of the model we are not here concerned but though a suspension of disbelief is called for it should be remembered that it is ever temporary. An energy balance leads to the equation for the temperature

\[
k_0 \nabla^2 T + (-\Delta H) \rho_b S \phi f(c_1, c_2, ..., c_S, T) = 0 \quad (2)
\]

where \( \Delta H \) is the heat of reaction and is credited with a negative sign since the exothermic reaction, being more interesting in its effects, is taken as the norm. The simplest of boundary conditions will be taken at the boundary of the pellet, namely

\[
c_i = c_{in}, \quad T = T_r. \quad (3)
\]

The notation for the basic equations is an obvious one with \( c_i \) immediately suggesting the concentration of the \( i^{th} \) species and \( T \) the temperature. Similarly the suffix \( f \) in the boundary value suggests quantities associated with the fluid phase around the particle or, for the teutonically minded, with the surface. As a problem grows one often runs out of really sympathetic letters for the various quantities and compromises often have to be made. However, when the obvious suggestiveness of an initial letter (e.g. \( c, T \)) is abandoned, those quantities that hang together should have letters that hang together; thus dimensionless \( c \) and \( T \) may become \( u \) and \( v \) but the barbarity of \( \Psi \) and \( W \) should be avoided. Well-
established conventions should be observed and of course there are publishers' house styles which may ultimately override a preference for Re and insist on N_Re. The practice of using two letters for one quantity is open to objection even though one in upper and one in lower case give it a pleasant literary favor.

However notation is somewhat a matter of taste and "de gustibus non est disputandum." Since it is also a vehicle of communication it is important not to become so attached to one's own version that the sensibilities of others are offended or communication impaired.

These basic equations presume a consistent set of units for each variable and parameter and our first task is to render the variables dimensionless. This does not derogate their physical significance in any way, for it is always important to keep the physical meaning of a variable or parameter in mind; rather it is intended to confer a meaning on their magnitude that is independent of the particular system of units. This point is important for the significance thus attained is universal in a deeper sense than would be conferred even by a universal agreement on units, such as the SI. Philosophically it is akin to Lonergan's independence of time and place [2]. But more than this, it measures the quantities in terms that are intrinsic to the problem rather than those dictated by an arbitrary external system. In general the objective should be to keep the dimensionless variables of the order of magnitude of 1 and allow the parameters to be just that—quantities which give the measure of the situation. However this should not be done at the expense of introducing unnecessary dimensions. For example, when the tubular reactor is considered without regard to any longitudinal dispersion there is no boundary at the far end of the reactor and it is artificial to introduce the length of the reactor just to make the dimensionless axial coordinate go from 0 to 1; it is preferable to use a combination of velocity and rate constant with the dimensions of length. It is however often possible to choose between putting a parameter in the equation or in the boundary conditions as we shall see later.

In the problem under consideration \( r = (x,y,z) \) is the coordinate system within the pellet of which we have some natural dimension, \( d_e \), to render these independent variables dimensionless as \( \rho = (\xi,\eta,\zeta) = r/d_e = x/d_e, y/d_e, z/d_e \). (Here a notational problem is raised by the traditional use of \( \eta \) for the effectiveness factor. We should probably go to \( (x_1, x_2, x_3) \) as coordinates with \( x_i = x_i/d_e \). However so little use is made of the cartesian space coordinates that we will not labour this. When there is symmetry and \( r \) can be taken as a scalar its dimensionless form is \( \rho \). It is dangerous to take \( u_i = c_i/c_t \) since we may want to consider \( c_{it} = 0 \) for some products of the reaction. Rather we take \( c_t \) as characteristic of the \( c_{it} \), perhaps as \( x_i c_{it} \) and set \( u_j = c_j/c_t, u_{it} = c_{it}/c_t \). Then equation (1) becomes

\[
\nabla^2 u_j + \frac{\alpha_j d_j^2 \rho_j S_j}{D_j c_t} f(c_j u_j, T) = 0, \quad (4)
\]

where the Laplacian is with respect to the dimensionless space variables. There is only one characteristic temperature in the data, namely \( T_r \), and it is in no danger of being zero. We therefore take \( v = T/T_r \) and the second equation is

\[
\nabla^2 v + \frac{(-\Delta H) d_j^2 \rho_j S_j}{k_t T_r} f(c_j u_j, T, v) = 0. \quad (5)
\]

The second terms in these equations is now dimensionless and could be written as say \( R_j(u,v) \) and \( R(u,v) \). However this would confound the importance of the various factors that enter the functions and overlook the fact that they are all proportional to one another. It is better to render the reaction rate dimensionless first by setting

\[
R(u,v) = f(C, u_j, T) / f(c_j, T_r) \quad (6)
\]

so that \( R(u_j, 1) = 1 \). Then the coefficient of \( R \) in equation (4) would be \( \alpha_j d_j^2 \rho_j S_j / D_j c_t \) and this only depends on \( j \) through \( \alpha_j \) and \( D_j \). If we let \( \Delta_j = D_j / D_e \) where \( D_e \) is some characteristic value of the diffusivities then \( d_j^2 \rho_j S_j f(c_j u_j, T) D_j c_t \) emerges as the characteristic dimensionless parameter. We will not rush to fix this characteristic value \( D_e \) since it may be advantageous to fix it—or rather the combination \( D_e c_t \)—later. But

\[
\phi^2 = d_j^2 \rho_j S_j f(c_j, T_r) / D_e c_t \quad (7)
\]
Our first task is to render the variables dimensionless. This does not derogate their physical significance in any way, for it is always important to keep the physical meaning of a variable or parameter in mind; rather it is intended to confer a meaning on their magnitude that is independent of the particular system of units. Philosophically it is akin to Lonergan's independence of time and place. But more than this, it measures the quantities in terms that are intrinsic to the problem rather than those dictated by an arbitrary external system.

is in fact the general form of the modulus introduced by Thiele and commonly bears his name. This is appropriate enough for of the three independent workers in the late thirties he solved this problem the most completely (see historical notes in 3, 4). Calling this parameter \( \phi^2 \) we have

\[
\nabla^2 u_i + (\alpha_i/\Delta_i) \phi^2 R(u,v) = 0 \quad (8)
\]

\[
\nabla^2 v + \beta \phi^2 R(u,v) = 0 \quad (9)
\]

where \( \beta = (-\Delta H) D_c c_i / k T_i \). These equations hold in \( \Omega \), the region occupied by the pellet, whilst on the boundary \( \partial \Omega \)

\[
u_i = u_i, v = 1. \quad (10)
\]

Let us pause a moment to see what we have. There are three dimensionless independent variables in \( \rho \) occurring explicitly only in the differential operator, \((S+1)\) dependent variables and one reaction rate expression, \( R \). There are \((S+2)\) visible parameters, of which \( S \) are stoichiometric coefficients modified by the diffusion ratios (it is assumed that none of these is zero). \( \beta \) is clearly a dimensionless heat of reaction, on which more later, and there may be one or more parameters, such as a dimensionless activation energy or Arrhenius number, concealed in the dimensionless rate law. The Thiele modulus can be written

\[
\phi^2 = d_v^s \rho_0 S_x^e (c_j r / T_i) / d_s^s D_e (c_i / d_v). \quad (10)
\]

The numerator is proportional to the total reaction rate at surface conditions since the volume is some multiple of \( d_v^s \). Similarly in the denominator \( d_v^s \) is proportional to the surface area and \( (c_i / d_v) \) characteristic of the gradients in concentration, so that the whole denominator is a measure of the total diffusion rate. The Thiele modulus is thus a ratio of the reaction rate to the diffusion rate and, when it is small, the reaction rate is the limiting whereas, when it is large, diffusion controls. But why call it \( \phi^2 \) rather than \( \phi \)? This is certainly legitimate since the Thiele modulus is always positive, but it is not altogether a product of hindsight. For the Laplacian is a second order operator and hence we might expect solutions to be functions of \( \phi \rho \), which is rather neater than \( \phi^2 \rho \).

But at this point the mind should question whether \((S+1)\) equations are really necessary when there is only one reaction in an adiabatic system. This is the import of the maxim “Think geometrically.” Geometry is here being used in a sense which is loaded with even more overtones than the \( \text{αγεωμετρητικός} \) over the archway of the academy. It embraces the idea of degrees of freedom and of what we may expect in the way of characteristic dependencies. In this case we observe that we can eliminate the reaction rate between any pair of equations and that the linear combinations \( (\alpha_i, u_i - \alpha v) \) are all harmonic functions. Since their values are constant on the surface \( \partial \Omega \) they are constant throughout \( \Omega \) and so each concentration can be expressed in terms of the temperature

\[
u_i = u_i + (\alpha_i / \beta \Delta_i) (v-1)
\]

This would allow us to reduce all the equations to a single equation in the dimensionless temperature.

However, once having perceived the idea of reducing the equations to a single equation, we might try to do the reduction more symmetrically. There is a risk here since it is sometimes an advantage to stay with a physical variable such as \( v \) rather than move to a more mathematical variable. Let us brave this danger in the hope of comprehending the mysteries of the equation and set

\[
u_i = u_i + \frac{\alpha_i}{\Delta_i} w, v = 1 + \beta w \quad (11)
\]

and

\[
P(w) = R(u_i + \alpha_i w / \Delta_i, 1 + \beta w). \quad (12)
\]

Then all the equations reduce to the single equation

\[
\nabla^2 w + \phi^2 P(w) = 0 \text{ in } \Omega \wedge w = 0 \text{ on } \partial \Omega \quad (13)
\]
But \( R(c,T) \) has a zero on the path

\[ c_i = c_{ir} + D_i c_{ir} \frac{\alpha_i}{D_i} w, \quad T = T_i + \left( -\Delta H \right) \frac{D_i c_{ir}}{k_a} \]

for either the reaction reaches equilibrium or, if it is irreversible, a least abundant reactant is exhausted. We may now choose \( D_i c_{ir} \) so that this corresponds to \( w = 1 \). Then if the reaction is irreversible, \( 0 \leq w \leq 1 \) since no concentration can become negative. If the reaction is reversible then \( 0 \leq w \leq 1 \) provided the reaction does not go beyond equilibrium and the rate change sign. Physical intuition would dispose one to doubt if the reaction could go beyond equilibrium but the following argument (due to Varma (5)) proves the case. For suppose there is a region \( \Omega \) within \( \Omega \) where \( w > 1 \) and \( P(w) < 0 \), then it is bounded by a surface \( \partial \Omega \) on which \( w = 1 \). But in \( \Omega \), \( \nabla^2 w = -\phi \beta P(w) > 0 \) and so \( w \) is subharmonic. This implies that \( w < 1 \) in \( \Omega \) and contradicts the assumption that \( w > 1 \) there.

We have reached the point of knowing that the system can be reduced to a single equation (13) in a variable \( w \) bounded between zero and 1; also the reaction rate expression \( P(w) \) has been normalized so that \( P(0) = 1, P(1) = 0 \). By equation (11) the fact that \( w \leq 1 \) implies that the steady state temperature cannot exceed \( T_r(1+\beta) \) a result which in its generality is due to Prater and justifies attaching his name to the parameter \( \beta \). It was the way in which Thiele expressed the useful result of the solution of the equation that distinguished his work from that which had gone before. The mathematician commonly uses a norm of the solution, which in this case might be \( \max \Omega |w| \), but the useful functional of the solution is not a norm but rather the average reaction rate as a fraction of the reaction rate at surface conditions. This is known as the effectiveness factor where \( V_p = \nu d^3 \) is the volume of the particle and \( dV = dV/d\rho^2 \) and \( d\Omega \) are the elements of volume of \( \Omega \) and area of \( \partial \Omega \) respectively. The external surface area of the particle is \( S_x = \sigma d^2 \) and \( \partial / \partial n \) denotes the derivative along the outward normal. Note that for any shape \( \eta \) will be a function of \( \phi, \beta \) and whatever parameters are concealed in \( P(w) \).

When the tubular reactor is considered without regard to any longitudinal dispersion there is no boundary at the far end of the reactor and it is artificial to introduce the length of the reactor just to make the dimensionless axial coordinate go from 0 to 1; it is preferable to use a combination of velocity and rate constant with the dimensions of length.

2. EXPLORING THE SOLUTION

Thus far we have only set up the equations that govern the system and it would be relatively safe to proceed immediately to the solution by some respectable numerical technique. We want, however, to get more of a feel for the form of the solution. To do this we can go in several directions:

a. simplify the geometry and with it the differential operator;

b. simplify the kinetics so that an analytical solution is possible;

c. use a crude numerical method;

d. consider limiting cases.

Let us consider these seriatim.

2a. SIMPLIFYING THE GEOMETRY

The simplest form of a Laplacian operator is the second order derivative in one variable. To make the equation one dimensional we may consider the case of a slab of porous catalyst with two exposed faces a distance \( 2d \), apart and with its other edges sealed. Then there is a single spatial variable \( \rho \), the dimensionless distance from the central plane and the exposed surfaces are \( \rho = \pm 1 \). To make things even simpler, we consider only symmetrical solutions for which the derivative vanishes on \( \rho = 0 \). Then the equations are:

\[
\frac{d^2 w}{d\rho^2} = -\phi \beta P(w),
\]

\[
\frac{dw}{d\rho} = 0, \rho = 0,
\]

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\[ w = 0, \rho = 1, \]  
\[ \eta = \int_{0}^{1} P(w) \, d\rho = \frac{-1}{\phi^2} \left( \frac{dw}{d\rho} \right)_{\rho = 1} \]  
(18)

Though the sphere could have an equally symmetrical solution and is more natural, since it does not need sealed edges, its Laplacian is more complicated and \( \rho \) enters explicitly.

The second order autonomous form of equation (15) suggests the phase plane might give some insight into the solution. Let \( W \) denote the derivative \(-dw/d\rho\), then

\[ \frac{dw}{d\rho} = -W, \quad w(1) = 0, \]  
(19)

\[ \frac{dW}{d\rho} = \phi P(w), \quad W(0) = 0. \]  
(20)

In the \( w, W \) plane this means that the trajectory \( w(\rho), W(\rho), 0 \leq \rho \leq 1 \), is a curve, such as LM in Figure 1, which starts \( (\rho = 0) \) at some point on the \( w \)-axis and ends \( (\rho = 1) \) on the \( W \)-axis.

The isoclines could be drawn in the plane and we could sketch the solution curves, but they would have to be redrawn for each value of \( \phi \). However \( \rho \) is only acting as a parameter along the solution curve and there is no reason why \( \phi \rho \) should not be the parameter instead. Let \( \phi \rho = \tau \), \( S(\tau) = w(\tau/\phi) \), \( S(\tau) = W(\tau/\phi)/\phi \) then

\[ \frac{ds}{d\tau} = -S, \quad s(\phi = 0), \]  
(22)

\[ \frac{dS}{d\tau} = P(s), \quad S(0) = 0, \]  
(23)

and

\[ \eta = \frac{1}{\phi} S(\phi). \]  
(24)

Now the isoclines can be drawn once and for all in the \( s, S \) plane, for suppose \( dS/ds = -\omega \) then

\[ \frac{dS}{ds} = -\frac{P(s)}{S} = -\omega \quad \text{or} \quad S = \frac{1}{\omega} P(s). \]  
(25)

But this means the isoclines are all derived from the curve \( P(s) \) which represents the reaction rate expression and that for a given slope \( \omega \) the curve for \( \omega = 1 \) is simply redrawn with a vertical scale of \( 1/\omega \). Let us suppose that the curve \( S = P(s) \) is like PQ in Fig. 2. Then it can be crossed with a number of short lines of slope \(-1\). The curve RQ whose ordinates are just twice those of PQ is ticked with lines of slope \(-1/2\), whilst TQ at half the height of PQ is the isocline of slope \(-2\). The s-axis and the vertical \( s = 1 \) correspond to infinite and zero slope respectively. Quite clearly then any solution curve such as LM will take off vertically from L and go in an arc of decreasing slope to M. In fact
if \( s_0 \) is the value of \( s \) at \( L \), the arc \( S(s) \) is given by:

\[ S^2(s) = 2 \int_S^{S_0} P(s') \, ds' \]

and \( M \) is the point

\[ S^2 = 2 \int_S^{S_0} P(s') \, ds' = [S(\phi)]^2. \quad (26) \]

Once this curve is determined the value of \( \phi \) which corresponds to it comes from the integral

\[ \phi = \int_0^{\phi} \, d\tau = \int_S^{S_0} \frac{ds}{S(s)} \quad (27) \]

Thus each trajectory can be made to yield a point on the \( \eta, \phi \)-curve by equations (24), (26) and (27).

But what can we learn of the behavior of \( \eta(\phi) \) without actually doing any of the integrations. First we see that for a solution curve \( L'M' \) lying underneath \( LM \) the corresponding value of \( \phi \) must be smaller. For the integral can be written

\[ \phi = \int_0^{\phi} S(\phi) \, dS = \int_S^{S_0} \frac{ds}{\omega(S)S} \]

and in comparing the contributions of the segments \( AB \) and \( A'B' \) to their respective integrals we see that \((-\omega)\) is greater on \( A'B' \) than on \( AB \) so that the integrand is smaller. Moreover the path \( LM \) is over a greater range of \( S \) than is \( L'M' \) so that on both counts the value of \( \phi \) corresponding to \( LM \) must be greater than that which corresponds to \( L'M' \). The trajectories cannot cross one another (except at \( Q \)) hence a sequence of trajectories with increasing \( s_0 \) give an increasing sequence of values of \( \phi \).

When \( \phi = 0 \) the equation gives the solution \( w = s = 0 \), so that \( s_0 = 0 \) corresponds to \( \phi = 0 \). Does \( s_0 = 1 \) correspond to \( \phi = \infty ? \) The answer must depend on the behavior of \( P(s) \) near its zero at \( s = 1 \). Let us suppose that \( P(s) = -P'(1)(1-s) + 0(1-s)^2 \) in the neighborhood of \( s = 1 \). Then the indeterminacy of \( dS/ds \) near \( s = 1 \), \( S = 0 \) is resolved by noting that

\[ \frac{dS}{ds} = -\frac{P(s)}{S} = P'(1)(1-s) \]

can be integrated to give

The trajectory that starts from \( Q \) therefore takes off tangentially to the line \( S = -\lambda(1-s) \) where \( \lambda^2 = -P'(1) \). If this is substituted in the integral (27) with \( s_0 = 1 \) we see that the integral diverges. It follows that the trajectory through \( Q \) (QN in Fig. 2) does correspond to an infinite value of \( \phi \). What is remarkable however is that the solution curve QN does not go to infinity but reaches \( s = 0 \) for a finite value of \( N \). This is clearly the case since if it sneaked up the \( S \)-axis it would have to have an increasingly large slope. But near the \( S \)-axis for large \( S \) the slope of the trajectories gets increasingly small, so that QN must finish at a finite point \( N \). Let the value of \( S \) here be \( S'_\infty \); then, since the trajectories \( LM \) move up under QN as \( \phi \) increases, \( S(\phi) \) approaches \( S'_\infty \) as \( \phi \) gets large. But equation (24) then shows that \( n \sim \frac{S'_\infty}{\phi} \) for large values of \( \phi \). Moreover the value of \( S'_\infty \) can be calculated from equation (26),

\[ S'^2 = 2 \int_0^1 P(s') \, ds' \]

Thus a rough sketch of isoclines can be made to yield a lot of information without really solving any equation. However, it should be mentioned that some of these arguments depend on the rather straightforward shape of \( P(w) \) and would not carry over quite so easily to a more general shape. In particular a family of nonintersecting curves of the type \( LM \) could be found, approaching \( 0 \) for \( \phi \to 0 \) and QN for \( \phi \to \infty \) but they would not necessarily correspond to a monotonic sequence in \( \phi \). The arguments about QN would also have to be modified if \( P'(1) \) were not finite.

2b. SIMPLIFYING THE KINETICS

The essential nonlinearity of the equations lies in the kinetic expression \( P(w) \) which is limited only by the normalization \( P(0) = 1, P(1) = 0 \). If we take an isothermal \( (\beta = 0) \) first order reaction \( P(w) = 1 - w \) and the equations become linear. In particular we have analytical solutions for simple shapes such as the sphere. In particular
\[
\frac{1}{\rho^2} \frac{d}{d\rho} \left( \rho^2 \frac{d}{d\rho} \left( \rho^2 \frac{dw}{d\rho} \right) \right) + \phi^2(1-w) = 0
\]  
(28)

\[w(1) = 0, \quad w'(0) = 0\]

has the solution

\[w(\rho) = 1 - \frac{\sinh \phi \rho}{\rho \sinh \phi}\]

(29)

Thus the effectiveness factor is

\[\eta = \frac{3}{\phi} \left[ \coth \phi - \frac{1}{\phi} \right]\]

(30)

which again has the asymptotic property that \(\eta \phi\) tends to a constant (in this case 3) as \(\phi \to \infty\).

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It is not suggested that the maxims or their illustration . . . provide an infallible recipe which when followed will open the portals of any problem. Rather, they are adumbrated as a framework.

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In this case the complete solution can be obtained rather easily and one might use this as a starting point to explore other variations such as those of shape or in the boundary conditions. In any case it ties in with what we learned from the method of isoclines about the general behavior of the planar case. From the simple form of solution we see that the value of \(w(\rho)\) rises from its zero boundary value with exponential sharpness near the surface \(\rho = 1\). In fact if \(\rho = 1 - y\)

\[w(\tau) = 1 - \exp - \phi \, y\]

so that \(w\) quickly rises to a constant value of 1 when \(\phi\) is large.

2c. COARSENING THE NUMERICAL METHOD

Often something can be learned from an extremely crude numerical method. This was first shown for this problem by Stewart and Villadsen [6]. At any rate for small values of \(\phi\), \(w(\rho) = \alpha (1-\rho^2)\) is an approximation that satisfies the boundary conditions for a symmetrical solution. We can deal with all three symmetrical shapes (the slab, cylinder and sphere) by writing the Laplacian as

\[\frac{1}{\rho^2} \frac{d}{d\rho} \left( \rho^2 \frac{dw}{d\rho} \right)\]

and with this trial function for \(w\) it is

\[-2(q+1)\alpha = -2(q+1)w(\rho)/(1-\rho^2)\].

Thus the differential equation would be satisfied at the point \(\rho = \rho_1\) if the value of \(\alpha\), and so of \(w_1 = w(\rho_1) = \alpha (1-\rho_1^2)\), were chosen to satisfy

\[2(q+1)w_1/(1-\rho_1^2) = \phi^2 P(w_1)\]

(31)

There is a full-scale theory, that of collocation methods, to say where the point \(\rho_1\) is best taken, but we can use our experience with the sphere in the previous section. When \(q = 2\), for the sphere, and \(P(w) = 1-w\), for the first order reaction, equation (31) gives

\[w_1 = \phi^2 (1-\rho_1^2)/[6+\phi^2 (1-\rho_1^2)]\]

Since the approximation should be good for small \(\phi\) we might hope that this would agree with equation (29) for small \(\phi\). In fact the expansions are identical in the first term \(\phi^2 (1-\rho_1^2)/6\) and agree in the term of order \(\phi^4\) if \(\rho_1^2 = 3/7\) or \(\rho_1 = 0.6547\). A more general analysis would show that \(\rho_1^2 = (q+1)/(q+5)\) is a good choice.

Let us use this value of \(\rho_1\) but return to a general \(P(w)\). Then with \(q = 2\), \(\rho_1^2 = 3/7\), equation (31) is

\[\frac{21w_1}{2\phi^2} = P(w_1),\]

(32)

Before exploring this equation let us note that to the same approximation

\[-\left( \frac{dw}{d\rho} \right)_{\rho = 1} = 2\alpha = \frac{7w_1}{2}\]

Hence, by (14),

\[\eta = \frac{21w_1}{2\phi^2} = P(w_1)\]

(33)

Equation (32) lends itself to a graphical solution, as is shown in Fig. 3, for the right hand side of the equation is the fixed curve \(P(w)\) and the left side the straight line through 0 of slope \(21/2\phi^2\). When \(\phi\) is small the line is steeply sloped, like 0A, and \(\eta\) is close to 1. In fact, if the part of the curve \(P(w)\) near \(P(0) = 1\) is approximated by the straight line \(P(w) = 1+P'(0)w\), then equation (33) can be solved for \(w_1\) and
\[ \eta = \left[ 1 - \frac{2P'(0)}{21} \phi^2 \right]^{-1} = 1 + \frac{2P'(0)}{21} \phi^2 + 0(\phi^3) \] (34)

On the other hand if \( \phi \) is very large the same kind of straight line approximation gives

\[ \eta = \frac{21}{2\phi^2} \left[ 1 + \frac{21}{2[-P'(1)]\phi^2} \right]^{-1} \]

This is not a very good approximation since we know that \( \eta \phi \) tends to be constant for large \( \phi \). However this is not surprising since \( w(\rho) = \alpha(1-\rho^2) \) is not a good approximation for large \( \phi \).

Much more important is the revelation of the possibility of multiple steady states that is made in Fig. 3. For if the curve \( P(w) \) is as shown then for values of \( \phi \) giving lines between OBC and OGH there will be three intersections such as D, E and F which will give three values of \( \eta \).

We cannot expect much accuracy beyond the point G, but Stewart and Villadsen showed that a surprising accuracy was maintained [6]. The important thing is that it gives notice of the multiplicity of steady states. Furthermore the variable \( w \), can be made a parameter in the computation of the \( \eta, \phi \)-curve, since \( \eta = P(w_i) \), \( \phi^2 = 21w_i/2P(w_i) \). This suggests that some internal value of \( w \), such as \( w(0) \) or max \( w(\rho) \) may be taken as the parameter along the \( \eta, \phi \)-curve in more general cases.

On the basis of this understanding computation by more exact methods, such as those described by Villadsen and Stewart [6] and Finlayson [7], can safely go forward. At the same time one must be cautious not to push conclusions based on crude approximations too far.

2d. CONSIDERING LIMITING CASES

The limiting cases of large and small \( \phi \) have already been considered in the partial solutions we have obtained. However they can be approached also from the equation itself. If \( \phi = 0 \), \( \nabla^2 w = 0 \) giving the solution \( w = 0 \) and \( \eta = P(0) = 1 \). Let us see if a solution can be generated in powers of \( \phi^2 \) by setting

\[ w(\rho) = \phi^2 w_1(\rho) + \phi^4 w_2(\rho) + \ldots \]

The function \( P(w) \) must be expanded similarly

\[ P(w) = 1 + \phi^2 P'(0) w_1 + \phi^4 [P''(0) w_2 + \frac{1}{2} P''(0) w_1^2] + \ldots \]

Then comparing powers of \( \phi^2 \) we have

\[ \nabla^2 w_1 = -1 \quad \text{in } \Omega, w_1 = 0 \text{ on } \partial \Omega \]

\[ \nabla^2 w_2 = -P'(0) w_1 \quad \text{in } \Omega, w_2 = 0 \text{ on } \partial \Omega, \ldots \]

These equations are linear nonhomogeneous equations and are easier to solve than the nonlinear equation (13). Moreover we can see the form which \( \eta \) will take, for first \( w_1 \), can be found and averaged to give \( k_1 \) (say), then \( w_2 \) can be found and its average, \( k_2 \), calculated, and so on. This then gives

\[ \eta = 1+k_1 P'(0) \phi^2 + \left[ k_2 P'(0) + \frac{1}{2} k_1^2 P''(0) \right] \phi^4 + \ldots \]

which accords with equation (34).

This solution for small \( \phi \) is obtained by a regular perturbation in powers of \( \phi^2 \) and a regular perturbation does not involve a change in the character of the equations. The situation for large \( \phi \) is quite different for, if we put \( \epsilon^2 = 1/\phi^2 \), we have

\[ \epsilon^2 \nabla^2 w + P(w) = 0 \] (36)

The limiting case \( \epsilon = 0 \) is here quite different for it has changed a second order differential equation into a non-differential equation \( P(w) = 0 \) whose only solution is \( w = 1 \). This makes sense since it claims that when \( \phi \) is large (i.e. the reaction rate is vastly greater than the diffusion rate) the reaction is virtually complete everywhere. But it cannot be true near the surface, for \( w = 0 \) on the surface itself and the solution is a continuous function of position.

This is the classic situation of a singular perturbation problem in which an “inner” solution—in this case a solution near the boundary—has to
be matched with an “outer” solution—in this case \( w = 1 \). Singular perturbation problems have a large literature [8,9,10,11] and this is no place to try to survey it, but mention should be made of the unusually lucid introduction that Segel and Lin [1] give in their book. In the present case we know from the experience of Section 2b that for large \( \phi \), \( w \) can rise with exponential sharpness from the boundary. In fact the solution we found there suggest that we should introduce \( \phi y \) where \( y \) is the normal distance from the boundary, as a new variable. This is known as a “stretching transformation” since it stretches \( y \) proportionately to \( \phi \).

If we introduce an orthogonal coordinate system in the boundary surface, say \( \xi, \eta \), and take \( \zeta = \phi y \) as the third coordinate then the Laplacian in equation (36) is

\[
\phi^2 \frac{\partial^2 w}{\partial \xi^2} + \nabla^2 w
\]

where \( \nabla^2 \) is a second order operator in \( \xi \) and \( \eta \). Substituting this in (36) and letting \( \epsilon = 1/\phi \) tend to zero gives

\[
\frac{d^2 w}{dz^2} + P(w) = 0.
\]

But this reduces the problem to the one dimensional case that we explored in Section 2a. Nor is this surprising since when all the change is confined to a thin shell on the outside of the pellet the curvature is not important and it might well be unfolded as a flat plate. Now the flat plate analysis gave

\[
[S(\phi)]^2 = 2 \int_0^1 P(s') ds'
\]

and when \( s_0 \) approaches 1, as in this case, \( \phi \to \infty \) and

\[
S \to S_\infty = \left[ 2 \int_0^1 P(s') ds' \right]^{1/2}
\]

But

\[
\frac{dw}{d\eta} = \frac{dw}{dy} = -\phi \frac{dw}{d\tau} = \phi S \sim \phi S_\infty.
\]

and so by equation (14)

\[
\eta \sim \sigma S_\infty / \phi
\]

This accords with all that has gone before. In particular if, for a sphere, \( d_0 \) is the radius \( \sigma = 4\pi, \nu = 4\pi/3 \) while for a first order reaction

\[
P(s') = 1 - s', \quad S_\infty = 1.
\]

Thus \( \eta \sim 3/\phi \) as we see also from equation (30).

CONCLUSION

The use of the phase plane and perturbation methods has been stressed in illustrating the value of the qualitative study of equations. These, of course, are not the only methods available—the maximum principles [12] and some of the theorems on the behavior of the solutions of equations come immediately to mind. Amundson’s papers in general, and some of those with Luss [13] and Varma [14,15] in particular, show how the skillful use of such tools can give insight into much more complicated systems than the one considered here.

It is not suggested that the maxims, or their illustration in the above example, provide an infallible recipe which when followed will open the portals of any problem. Rather are they adumbrated as a framework within which one aspect of the craft of mathematical modelling may be

“The exercised in the still night
When only the moon rages
And the lovers lie abed
With all their griefs in their arms.”

Sufficient will be the reward if for a few moments we find that it is “by singing light” that we have haply laboured.

REFERENCES


SUMMER 1976

ACKNOWLEDGMENT

A preliminary version of this paper was given as a seminar in the UNESCO project of postgraduate education (VEN 31) at the Universidad Oriente, Puerto la Cruz, Venezuela under the local coordination of Prof. Hassan Elmayergi. It is a pleasure to record my indebtedness to Ray Fahien for many valuable conversations in which we probed the nature of the mathematician's "magnificent grasp of the obvious." I am also indebted to Professor Arvind Varma for some valuable comments.

Mathematics Applied to Deterministic Problems in the Natural Sciences

By C. C. Lin and L. A. Segel
MacMillan, New York, 1974
Reviewed by R. Aris, University of Minnesota

It is generally agreed that it is all very well to teach students the methods of solving different types of equation, but that it is much more difficult—yet even more essential—to teach them how to develop a mathematical model, to assure themselves of its reasonableness and to get as much insight into it as possible before trying to compute a solution of its equations. Of the available books on the methods of applied mathematics the one under review is unique in addressing the more difficult task without neglecting the easier. As an introduction to the craft, as well as to the skills, of the applied mathematician it is as distinguished and valuable as the distinction and accomplishments of its authors would, in any case, lead us to expect.

Like that well-known province of the Roman empire, "liber est omnis divsa in tres partes." The first part introduces the scope and range of applied mathematics in a dramatic fashion by outlining the way in which the physical descriptions of galactic structure and the chemostatic behavior of slime mold amoebae lead to challenging mathematical problems. Deterministic systems and the generation of ordinary differential equations and random processes and their connection with partial differential equations are the subjects of the next two chapters and Fourier analysis, illustrated by problems of heat conduction, that of the two that follow. These five chapters provide a survey of the interaction of mathematics with physical phenomena for, besides those mentioned above, planetary orbits, the pendulum, Brownian motion, coagulation, twisted beams and DNA molecules all come into the picture. Nor are the mathematical notions confined to the pedestrian, for the authors do not hesitate to take up Poincaré's perturbation theory of periodic orbits and allude to the Gibbs phenomenon.

The second part of the book would be called, in the argot of our day, "very unique" for here some of the fundamental modes of applied mathematical thinking are explained in detail. Indeed the detail is often "painful," not in the contemporary connotation but in the older and more honorable sense of 'painstaking.' I know of no other place where the beginner and proficient alike will find a systematic account of the way in which the model and its equations should be handled and of how intelligent simplifications, dimensional analysis and the understanding of scale can be used to bring the problem into its most responsive form. This is the foreplay of mathematical analysis and, as might be anticipated by analogy, calls for sensitivity and intellectual tact. These techniques are admirably illustrated by formulating and solving a problem in osmotically driven flow. But the second part also contains a chapter on regular perturbations and an introduction to singular perturbation theory that is a model of all that an elementary exposition of a deep subject should be. Chapter 10 takes this exposition
further by treating Michaelis-Menten (or Langmuir-Hinshelwood-Hougen-Watson, not to mention Briggs and Haldane) kinetics in detail. Finally the phase plane, multiple scale expansions and linearization are introduced in connection with the simple pendulum.

After the virtuosity of this second movement, the third movement (just to mix my metaphors absolutely and uniformly) is relatively traditional. It provides an introduction to the theory of continuous fields and their associated partial differential equations, considering first the elastic vibrations of a bar, then continuum mechanics and inviscid flow and, finally, potential theory with an acoustical example. In a second volume we are promised more continuum mechanics, with Cartesian tensors viscous flow and elasticity, dispersive wave theory and variational methods.

In short it is a book that can be recommended without reservation both for its style and content. It can be recommended for chemical engineering courses; for the chemical engineering student—the least parochial of the engineering family—will welcome the catholicity of example which the chemical engineering teacher will find much instruction in working up further examples of his own.

An Introduction to Nonlinear Continuum Thermodynamics

by Gianni Astarita
Societa Editrice di Chimica, 133 pp.

Reviewed by Martin Feinberg,
University of Rochester

Since the turn of the century anyone who has set pen to paper in an attempt to advance thermodynamics has come under attack from one quarter or another, and the only thing upon which we all agree is that Gibbs was a very smart fellow. So, not knowing what to make of the battles raging around us, we opt for neutrality: we confine our teaching to the substance and style of 19th century thermodynamics. Although this course of action has served us reasonably well and, incidentally, lends the subject an undeniable charm, at some point we must ask if such a state of affairs is to prevail forever.

It might be argued that, before we commit our classrooms to anything new, we ought to sit back and wait until the relative merits of various 20th century theories are settled by experiment. Well, I don’t think things work that way for a subject as broad in scope as thermodynamics. What happens, I suppose, is that a theory is offered by Professors A, B, and C, is learned and found compelling by Professors X, Y, and Z, who in turn teach the theory to students, write textbooks, try their best to make converts of colleagues, and so on. If the theory has appeal and/or the political climate of the day is favorable, it penetrates into and diffuses through the mainstream of scientific thinking and ultimately flourishes if, in a sense difficult to make precise, that theory is “successful” in applications.

In 1963 Bernard Coleman and Walter Noll published a paper1 which articulated a simple, yet powerful, line of thermodynamic reasoning based upon the Clausius-Duhem inequality and, by way of example, demonstrated how that line renders results for familiar classes of materials—e.g., linearly viscous fluids which are Fourier heat conductors. In 1964 Coleman published a remarkable paper2 in which he used the methods proposed a year earlier to deduce results for materials with fading memory (e.g., polymer solutions and melts). Since then the theory has been explored and used extensively by others (notably Gurtin) in an explosion of papers generally endowed with high technical excellence. One can never be certain of these things, but I believe the body of theory precipitated by the Coleman-Noll paper of 1963 will, in fact, be “successful” and will come to play a permanent role in the way chemical engineers think about thermodynamics.

If this is so, then Professor Astarita’s monograph must certainly be regarded as an important step in the coming assimilation process. Although it is not the first volume which describes modern methods based upon the Clausius-Duhem inequality, it is, I believe, the first written by a chemical engineer with other chemical engineers predominantly in mind. As such, the book is likely to be a critical, if not decisive, factor in the manner with which our colleagues and students respond to the theory, at least in the immediate future.

Before I discuss the monograph in detail, let me state my own biases plainly. I admire the work Astarita admires, probably for the same reasons. Plausible premises are stated clearly at the outset (to be accepted or rejected as one sees fit) and conclusions are drawn from these using standards of logic, rigor, and linguistic precision normally insisted upon in all other areas of science we deem Continued on page 133.
Professor Alkire studied Chemical Engineering at Lafayette College and at the University of California at Berkeley. He has been on the faculty of the University of Illinois since 1969. In addition to teaching, he carries out a research program in the area of electrochemical engineering.
### TABLE 2: Demonstration Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soapmaking</strong></td>
<td>Soap is prepared from lye and lard by the assistant following the instructions on a lye bottle purchased in a grocery store.</td>
</tr>
<tr>
<td><strong>Nucleate vs. Film Boiling</strong></td>
<td>A copper tube containing a thermocouple is immersed in liquid nitrogen and the cooling curve is recorded on a strip-chart. The tube is then removed and coated with a thin layer of vaseline and immersed again. The insulated tube cools faster because nucleate boiling occurs instead of film boiling.</td>
</tr>
<tr>
<td><strong>Cooking Hot Dogs</strong></td>
<td>A thermocouple is inserted along the axis of a hot dog which is plunged into boiling water, and the increase of temperature at the centerline is recorded and compared with theoretical unsteady-state heat conduction calculations.</td>
</tr>
<tr>
<td><strong>Time Bombs</strong></td>
<td>Cans are prepared according to instructions in the reference and filled with natural gas. The gas is ignited and the time before explosion is recorded and compared with theoretical models.</td>
</tr>
<tr>
<td><strong>Polyurethane Foam Demonstration</strong></td>
<td>Ingredients from a commercially available foam kit (Mobay Chemical Co., Penn Lincoln Parkway West, Pittsburgh, Pa. 15205) are mixed and the exothermic process occurs. After two minutes the foamed plastic is rigid.</td>
</tr>
<tr>
<td><strong>Nylon Rope Synthesis</strong></td>
<td>6-10 Nylon is synthesized from sebacoyl chloride and hexamethylenediamine by interfacial condensation. The nylon skin is removed from the interface, forming a rope, and is wound upon a rod.</td>
</tr>
</tbody>
</table>

The demonstration experiments which accompany the lectures are outlined in Table 2.

The first lecture emphasizes the economic need for chemicals and how a ChE background gives access to many business areas in addition to the purely technical aspects which are seen by the students in coursework. An introduction to the department is always of interest: the layout of the building and labs, the faculty size, number of students in the curriculum, the nature of employment and salaries of recent BS graduates, and the fraction going on to graduate education. A list of trade periodicals (CEP, C&E News, etc.) is provided along with the library location and procedures. It is also useful to provide information about applications for scholarships and loans which might be available.

Lecture Group (a) emphasizes three characteristics of chemical engineering:

- Ch.E.’s understand chemical reactions.
- Ch.E.’s know how to separate chemicals.
- Ch.E.’s know how to carry out processes on a large scale.

Slide presentations are used to show flow sheets and process equipment. Nitrogen fixation is a good example since ample material is available [1] to illustrate all three points. The manufacture of synthetic rubber is also well-documented [2] so that a slide presentation can be prepared. As a change of pace, a discussion on making moonshine [3] gives a good opportunity to point out dilemmas involving materials of construction, siting the facility, process engineering, production problems, quality control, marketing strategies, and ultimate plant recovery. The production of penicillin [4] is always impressive owing to the conditions under which the process was developed. The small-scale home preparation of soap [5] (Expt. #1, performed in class) can be compared with commercial manufacture of detergents.

**IMPORTANCE OF INTUITION**

Lecture Group (b) consists of examples ranging from R&D to marketing. The discussion of research emphasizes the importance of intuition and the ability to predict and to scale-up. Experiment (2) (nucleate vs. film boiling) usually tricks the student’s intuition and leads nicely to a discussion of optimum heat exchanger fin design [7]. Results from Experiment (3) (cooking hot dogs) can be compared with unsteady-state heat conduction calculations for a rigid solid [8]; agreement within 10% is usually obtained. Experiment (4) (time bomb) is especially impressive [9] and demonstrates scale-up criteria by mathematical modeling. It is important to emphasize the value of graduate education for those interested in R&D endeavors.

Process evaluation and optimum design is nicely illustrated by the design of an overland sulfur transportation system [10]. To stimulate the imagination, Experiments (5) (polyurethane
foam) and (6) (nylon synthesis) are good examples for drawing out further discussion. Problems of designing around hazards [15], and analysis of plant failures [16] always makes a sobering impression of the energy contained in chemical plants.

Plant operation, process engineering and process management topics can be brought out through presentation of slides of process equipment. For example, I obtained from a campus recruiter a detailed sequence of several dozen slides involving a pipe-still furnace. Of special value at this stage in the course would be a field trip to a local production facility.

Marketing, sales engineering and higher-level management are areas where the importance of communication skill, personal style and business acumen can be emphasized. It has been difficult to obtain ancillary material for this portion of the course, and I rely upon personal experience.

Lecture Group (c) is based primarily upon materials contained in Ref. [17]. A good starting point is the discussion of different perceptions of advantageous routes for carrying out chemical reactions as viewed by a chemist versus a chemical engineer (Chpt. 2, Ref. [17]). The dichotomy emphasizes once again the chemical engineer's concern about large scale processing with impure substances under economic and safety constraints. For example, the evaluation of five different process routes for phenol production provides a good basis for extended discussion. Economic aspects of choosing different reaction paths (Chpt. 2, Ref. [17]) is impressive to students since it demonstrates the narrow profit margin involved in large-scale production. Related aspects include uncertainty of feedstock price, sudden application of pollution standards on by-product disposal, development of new processing technology, the economic nature of the market for the product, and establishing the optimum return on investment needed for competitive survival. Once the best process route is chosen, a discussion of species allocation and flow sheets (Chpt. 3, Ref. [17]) demonstrates the importance of common sense and good engineering intuition, including an awareness of corrosion and classical physical chemistry. An introduction to simple material balances is always of interest since the students know that the next ChE course will begin at this point. Once the process flow sheet is developed, the problem of choosing the best separation method provides another basis for a common sense approach (Chpts. 4 and 5, Ref. [17]).

Lecture Group (c) often motivates students by demonstrating the importance of learning their engineering and scientific fundamentals in order to develop their intuitive prowess. It becomes abundantly clear that the act of defining technical problems is central to good engineering, and that that act requires application of the scientific method, common sense, and economic awareness.

**ADDITIONAL TOPICS**

Several additional topics can be salted into the foregoing outline as the mood of the class dictates. An important topic is graduate education; students are usually interested in engineering, business, medicine and law. I outline the time-scale for making these decisions, mention the different financial arrangements involved and, within engineering, describe the different styles which departments may have respect to graduate program, the better students often begin thinking about their next move at this time. For detailed examples of research in engineering, I draw upon my own program and sometimes invite a graduate student to give a short presentation of his research topic.

Another topic concerns departmental affairs in which freshmen can participate such as A.I.Ch.E. Student Chapter Meetings. We also have an Engineering Open House for which freshmen often prepare demonstration experiments as a basis for their term paper. Such activities often create a sense of identity and pride which sustains student interest in ChE in face of challenges in other coursework.

**EXPERIMENTAL RESULTS**

The course has been presented four times with class sizes ranging between 23 and 75 students. There was no difficulty in stimulating class discussion even with the larger class sizes. Students from other departments constituted about 14% of class enrollments.
The letter grading of the course is necessary because it is a required course. The grade is usually based on homework (50%), term paper (25%) and plant trip report (25%). Because the plant trip is not required for the course, those students who do not attend are asked to imagine what they would have seen and submit a brief report of their imagined observations. The average grade distribution to date has been: A-53%, B-30%, C-11%, D-3%, E-3%. I suggest that the D and E students drop ChE, and that the C students think carefully about their career choice. Grading by pass-fail would be attractive if it were possible.

Homework problems were chosen so that the students had the opportunity for extended pursuit of the problem if they wished. For example, instructions were provided for the home-made production of soap by the batchwise process demonstrated in class in Experiment (1); in addition, the chemistry for a two-step (hydrolysis/neutralization) process was provided. Students were asked to evaluate which process makes it possible to design for continuous, not batchwise, operation, to estimate production rates for one million people, to develop a flow sheet for a continuous process and discuss the overall engineering design. Three or four homework problems were usually assigned during the semester. The response was very conscientious, with the better quality problems often running ten pages of discussion.

In defining the term paper, the students were instructed to choose any appropriate topic which interested them and pursue it in whatever manner they saw fit. I offer to help discuss paper content if the students come to me with a topic in mind. The papers were surprisingly articulate, well-poised and conscientiously executed. In many cases, students performed experiments, did calculations or literature reviews, and submitted physical props in support of their work. Preparing the term paper was the most valuable experience to many because it got their feet wet.

A teaching assistant is essential for preparing lecture demonstration experiments, grading, and developing course improvement topics. For the range of class sizes encountered, a single assistant was adequate.

The course content, including slides and demonstration experiments, was developed without excessive effort in a period of about six months. During this time the ChE trade journals were scanned regularly, along with the standard texts on chemical processing. The major difficulty was in developing demonstration experiments and obtaining slide sequences of process facilities.

A crucial aspect of the course lies in sensing the mood of the class, and not proceeding too quickly into detailed discussion if their interest is not yet aroused. Because the course met only once a week, each lecture had to be complete in and of itself.

Although it is difficult to measure success of freshman courses, one can claim that the retention of freshmen into the sophomore year is a useful measure of whether the course succeeds in developing interest in the curriculum. For the six years prior to offering the freshman course, the average retention of second-semester freshmen into the sophomore year was 57%. For the period during which the course has been offered, 86% of the students who took the course continued into the next semester in ChE. Although such data are influenced by any number of other factors, it seems reasonable to suggest that the course has contributed to increased retention to a considerable extent.

SUMMARY

A one-hour freshman course for chemical engineers has been developed in order to provide qualitative information upon which career decisions may be made by students. Discussion topics, including lecture demonstrations, are chosen to illustrate the wide scope of ChE activities. Students have open-ended avenues of response through homework and term projects.

Freshman courses could also be built around the development of quantitative skills through which insight into engineering methods may be gained. However, with respect to the goal of career orientation, the development of quantitative skill to sufficient depth would be difficult to achieve in a one-hour course. The qualitative

Continued on page 145.
PLANT DESIGN: A LOGICAL FIRST COURSE FOR CHEMICAL ENGINEERING FRESHMEN

RONALD A. SHELDEN
University of Maine
Orono, Maine 04473

At many universities the once monolithic common core of studies for beginning students is crumbling. There is a widespread feeling that students should not have to wait for as much as two years to come into close contact with their department and chosen discipline, and that this delay is an important contributor to the loss of students from engineering during the first two years of study. Once the decision is made to make available to engineering freshmen a course in chemical engineering, the obvious next question is... during much of their training, students will not receive or at least will not perceive an integrated experience. I believe this lack of... seeing how all the parts of their training fit together... is a major factor in what students perceive as a lack of relevance...

what this course should be. Perhaps it should be plant design. Recently in this journal Gordon Youngquist [1] wrote of his experiences with a freshman course in plant design at Clarkson College. I would like to describe my own experiences with a similar course at the University of Maine. Most ChE departments offer a plant or process design course as an integrating experience in the senior year. Its placement in the final year of study seems reasonable in that the student at that point has the most knowledge to integrate. But implicit in that decision is the idea that during much of their training, students will not receive or at least will not perceive an integrated experience. I believe that this lack of integration—of seeing how all the parts of their training fit together and further their career development—is a major factor in what students sometimes perceive as a lack of relevance in their training.

The students also may not have a clear idea of the systems aspect of the chemical process, i.e. that there are interactions between process elements such as the reactor and the separator, and that optimal design requires examination of the system as a whole. Finally, the student may lack a clear idea of the role of economic considerations in reaching optimal engineering decisions. (They may as a result fail to elect courses in economics from the smorgasboard of humanities and social studies electives we offer them.) Plant and process design courses are excellent vehicles for remedying these problems, but they come late. I wished to test the idea that by studying the design of a very simple chemical process in their freshman year, students could obtain these important insights at the start of their studies rather than at the end.

At the University of Maine, ChE freshmen all take a two-semester course “Introduction to Chemical Engineering” in which they select and work on a number of laboratory projects from among those offered by the department. The projects are designed to introduce them to the practice of chemical engineering. Each project lasts about four weeks, and the students work on a total of six during the year. As one of the projects, I offered the design of a chemical plant, and I taught this to three different groups during one semester in the Fall of 1975. The groups met one afternoon each week for four hours. There was no homework assigned other than the preparation of a final report by the group. There were no formal examinations.

There were six to nine students in each group. We met around a table in a room which did not have a blackboard. There was about one hand or desk calculator per two students. I believe that all of these elements—small groups, calculators, an informal setting, close contact between instructor and students—were important positive factors. The electronic hand calculator, for
example, is working a quiet revolution in engineering studies. The number and kinds of calculations that we could carry out in a short period of time was very much influenced by the availability of these instruments. The absence of a blackboard helped in keeping our sessions from degenerating into the lecture format. There was a great deal of “eyeball contact” and it was not difficult to keep everyone involved. The instructional method used involved a combination of questioning and guiding. Calculations were carried out simultaneously at several places around the table. Feed-back, the detection and correction of errors, was immediate.

THE BASIC SCENARIO

During the first session with each group we developed the basic scenario. The process might best be described as a “let’s pretend” game in which everyone participated. I began by proposing that we wished to react A and B in a chemical plant and sell the product. “What do we need to know to design the plant?” With some coaxing and guiding the students began to ask the necessary questions and to provide the answers. The basic chemical plant developed in each case consisted of a reactor and a separator. In the separator the unreacted A and B were removed from the final product C and recycled to the reactor. In one project the separator was an evaporator. In the others it was a filter. The reaction was second order, and irreversible. Did we need to know the rate of reaction and how it varied with concentration? We discussed the kind of experiment we would carry out to obtain this information and then we imagined the result!

Ronald A. Shelden studied chemical engineering at the City University of New York (B.Ch.-1958) and Princeton University (Ph.D.-1964). He did post-graduate research at the Milan Polytechnic in Italy, and Kyoto University in Japan. He has taught at Tufts University, the University of El Salvador, and, as a UNESCO adviser, at the Catholic University, Santiago, Dominican Republic. Dr. Shelden is now an associate professor in the chemical engineering department at the University of Maine at Orono. His present major research interest is techno-economics.
TABLE 1. RESULTS OF STUDENT SURVEY.
THERE WERE 17 QUESTIONNAIRES RETURNED; 23 STUDENTS TOOK THE COURSE.
RESPONDENTS WERE ANONYMOUS.

<table>
<thead>
<tr>
<th>Question</th>
<th>Excellent</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, how would you rate the value of your experience in plant design?</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2. How would you rate the project as an introduction to the role of economics in chemical engineering?</td>
<td>7</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3. Do you feel that the project gave you a good understanding of how your future courses fit together, and the purpose of each one?</td>
<td>3</td>
<td>9</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4. How would you rate the project in terms of helping you to understand the work of the chemical engineer?</td>
<td>6</td>
<td>8</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5. What percentage of the work we covered do you feel you understood?</td>
<td>range 75 - 100</td>
<td>mean 87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Do you think that a course in plant design would be a good first course for chemical engineers?</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Using approximate Lang factors [2], we could estimate the cost of the plant from the cost of the major pieces of equipment. The students were then able to compare the relative advantages of batch and continuous operation, at least in terms of the higher initial equipment costs for the latter and the higher estimated labor cost for the former. How should these costs be compared? We discussed the concepts of depreciation and marginal return on investment, and carried out the necessary calculations. The students also examined the interaction between the demand curve for the final product and the engineering design calculations in determining the optimum size for the plant. In every project they were able to see the role of economics in determining what constitutes an optimal design.

Although we did not determine, for example, the size of pumps, the students understood that pumping costs could be an important factor in determining the optimal conversion and hence the optimal design. I explained that they would learn how to determine the pumping requirements in their future course work in fluid dynamics. Similarly, I tried to show how their other future courses would meet specific needs that suggested themselves during our design work, but which we did not have time to treat.

IN RETROSPECT

HAD TIME PERMITTED, if this were a full semester course rather than a 1/3 semester course, we could perhaps have included a recycle pump, a recycle heater, or even a distillation column as the separator. We might have attempted programming the calculations and finding the optimum design rather than comparing just a few designs. The possibilities are exciting.

I feel that the course accomplished several important objectives.

- I think the students now have a better understanding of the curriculum they will follow. They saw the kinds of things one needs to know to design a chemical plant.
- They learned that in general we have to consider the whole system if we are correctly to design any of its parts.
- They gained a better understanding of the role of economics in engineering decision-making, and of what we mean by an optimal solution.
- They obtained a clearer view of the meaning of chemical engineering as a discipline, and the factors that set it apart from, for example, chemistry.
This is of course a great deal to claim for one short course, and one may well ask whether simply going through the calculations together with their instructor constituted a significant learning experience for the students. My own impression is that we were able to keep together as a group, and that student comprehension was good—surprisingly good. The students themselves, when surveyed several weeks after the course was over and the final grades were in, indicated that they had understood most of what we covered (see survey results below). On the basis of the written final reports they prepared presenting their results, and our close contact in class, I feel their evaluation is substantially correct.

I think the experiment was very encouraging, and that the idea of offering freshmen a course in chemical plant design well merits consideration.

REFERENCES


BOOK REVIEW: Astarita

Continued from page 125.

"mathematical." Moreover, originators of the theory offer no promises of insight into structure and evolution of living things, of the stability of societies, or of anything else so grand. Indeed, their interest in the past few years has been focused not upon thrusts toward trendy applications, but rather upon critical and scholarly re-examination of existing theory.

I appreciate all of this, and that is why I was predisposed toward Astarita's viewpoint before the book was sent for review. It is also for this reason that, upon reading the book, I probably reacted more sharply to shortcomings than would someone less interested in its success. Before I describe the book and point out what I think are its blemishes, let me state in unequivocal terms that I think Professor Astarita has made a bold and important contribution to our literature and, considering the brevity of the book, has rendered a surprisingly effective exposition of difficult material. He has served us well.

Chapter 1 is devoted to mathematical preliminaries. Readers who have not been exposed to mathematics required for, say, a graduate course in fluid mechanics are not likely to find this chapter adequate; on the other hand, readers who have had this exposure but little more will find it helpful. Some of the "preliminaries" offered (orthogonal tensors, covariant and contravariant components of vectors and tensors) are never used in the book and might just as well have been omitted.

Chapter 2 is similar to the first chapter of Truesdell's monograph insofar as it tentatively deals with thermodynamics of homogeneous systems, primarily as a vehicle for sketching the Coleman-Noll methods.

In Chapter 3 the familiar field equations for balance of mass, momentum, and energy are discussed, the local form of the Clausius-Duhem inequality is placed alongside these as a thermodynamic postulate, and the stage is set for demonstration of how that inequality serves to place restrictions upon constitutive equations.

In Chapter 4, application of the theory is demonstrated through successive consideration of ideal fluids, viscous fluids, and elastic solids—all regarded as heat conductors.

Chapters 5 and 6 are devoted to Coleman's study of implications the Clausius-Duhem inequality has for materials with fading memory. The development is closer in technical detail to Day's exposition of the same subject then it is to Coleman's 1964 paper.

In discussing what I regard to be the book's weaknesses I should point out that these are more tactical than they are technical. It is important to make a distinction between, on one hand, the methods introduced by Coleman and Noll in 1963 and, on the other hand, Coleman's application in 1964 of those methods to materials with fading memory. The first should, I think, be given clear priority in an introductory work; fortunately, the methods are brilliant in their simplicity and can be taught clearly without much need for advanced mathematics. The second is likely to interest a more limited audience and requires such delicate functional analysis that any brief treatment intended for chemical engineers must, of necessity, be more suggestive.
A Freshman Course

A PRACTICAL INTRODUCTION TO ANALYSIS AND SYNTHESIS

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An elementary treatment of differential equations is being used as the thread from which to weave the fabric of an introductory course in chemical engineering for freshmen at the University of Arizona. The basic philosophy of the course is to introduce students to as many elements of ChE as possible, but in a unified way in order to preserve coherency. In a series of demonstration experiments, students exercise the process of analysis by applying a mathematical model to experimental data obtained. Experiments have been chosen which follow first order mathematics for simplicity since most of the students are concurrently enrolled in calculus. The use of experiments which follow a single mathematical algorithm, in an approach similar to those of Shair [1] and Gerrard [2], also has the advantage of demonstrating analogies which exist among quite different phenomena. Concepts illustrated include dimensional analysis, scaleup, energy conservation, heat transfer, mass conservation, mixing, and chemical reaction, though many other equally good experiments could be used.

Other concepts which are introduced are the difference between empirical and semi-theoretical modeling, shell balances, the distinction between lumped and distributed parameter systems, the distinction between steady state, unsteady state, and equilibrium, and the use of various items of equipment to obtain process data. The choice of experiments was also influenced by the desire to utilize most of the elements of analysis demonstrated in the first part of the course in the synthesis of part of a process design as the last course assignment. This last assignment involves some computer programming which is a reinforcement of the FORTRAN studied in the previous semester.

BASICS AND EMPIRICAL MODELING

The semester is begun by introducing some tools which are useful later in the course. These include the correct use of units and dimensions and graphing on various kinds of graph paper (cartesian, log-log, and semi-log). While in the area of dimensions, dimensional analysis is covered. The goal in this exercise is to illustrate a systematic method for empirical modeling in an efficient manner. In one homework assignment, students determine the dimensionless groups necessary to predict what will happen in mixing a liquid in a large unbaffled tank by doing experiments in a smaller one. How this works in practice is then demonstrated in class by using the Reynolds and Froude Numbers to predict at what mixing speed air entrainment will occur in a large unbaffled vessel using data from a smaller one. For this purpose a sugar solution is mixed in two different sized glass beakers agitated with magnetic stirring bars. Mixing speed is measured with a strobe light. This is related to practicality by mentioning that air entrainment often results in frothing. As an aside, it is also effective to show what happens when the vessels are baffled.

MECHANISTIC ANALYSIS

Following this venture in pure empiricism, the notion of mechanistic modeling is introduced. The mathematics used is simply the first
order ordinary differential equation of the form below.

\[ \frac{dy}{dx} = a \ (y + b) \quad (1) \]

\[ y(x = x_0) = y_0 \]

This is very carefully introduced and related to their calculus background. The solution is then derived in the logarithmic form.

\[ \ln \left[ \frac{y + b}{y_0 + b} \right] = a \ (x - x_0) \quad (2) \]

Students who are taking pre-calculus math or who are otherwise uneasy about this material are assured that it is correct and if they want, all they need do is memorize it at this point since it will be used several times in the exercises to come. The utility of semi-log graph paper in determining the coefficient (a) becomes evident at this point.

The first semi-theoretical modeling experience involves the use of a material balance on a tracer to determine if a continuous flow, stirred tank is perfectly mixed. The unsteady state material balance is derived by the finite element approach. The analogy of this equation to the mathematical form given by equation 1 is demonstrated and the solution to the equation is written. Experimentally a red dye is injected into a small glass, magnetically stirred tank and the effluent concentration is monitored by use of a Bausch and Lomb spectrophotometer fitted with a continuous flow cell [3]. Students are assigned the task of determining from the data whether the tank is perfectly mixed or not.

Next in the sequence comes the analysis of heat transfer from a hot fluid flowing through a circular tube. Again the finite element method is used, this time using the principle of conservation of energy. The concepts of heat transfer, heat transfer coefficient, and plug flow are discussed. The resulting differential equation is compared to equation (1) and the solution is written. Experimentally, hot air is blown down an aluminum tube which contains several thermocouples placed along its axis. At steady state the axial temperature profile is determined by a multipoint digital temperature indicator and the students are asked to determine the heat transfer coefficient.

The last demonstration experiment is to determine the reaction rate constants for a pseudo first order chemical reaction in a batch reactor. The glass vessel used in the mixing experiment is now used as the reactor since we have determined that it is well mixed. The reaction employed is the alkaline fading of phenolphthalein (4). Since there is a color change associated with the reaction, the Bausch and Lomb spectrophotometer is used to monitor the reaction progress. This reaction is reversible so that the color never completely disappears as equilibrium is approached. Using the data generated, students are asked to determine the forward and reverse reaction rate coefficients in a graphical manner analogous to the way previous experiments were handled.

**DESIGN SYNTHESIS**

**BY THIS TIME** the semester is nearing the end. After a discussion of process synthesis, a specific process design case is presented. To date, the case used has been the manufacture of detergent by an exothermic benzene alkylation reaction in a continuous, stirred tank reactor. This situation is a little different from any previously covered, and combines the elements of heat transfer to a coil, material conservation, and chemical reaction in order to determine the annual cost as a function of such variables as reactor temperature, conversion, and exit cooling water temperature. This study effectively summarizes the semester and introduces the method of synthesis for process design. In doing this the students write FORTRAN subroutines for the reactor analysis and coil analysis which must conform to a specified format so as to interface with an executive program given to them. This allows them to see some of the advantages of programming with subroutines which include versatility (use of a subroutine over and over again), ease of debugging, and allowing several persons to be involved simultaneously in solving a problem by computer by working on different but compatible parts.

**CONCLUSION**

This course has been presented in this manner for two successive years. Student reception
A Freshman Course

PROCESS MODEL-BUILDING: AN INTRODUCTION TO COMPLEX DESIGN

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THE ENGINEERING SCALE model is more than a publicity ornament or marketing aid. It is used in all phases of project engineering from concept evaluation through design and construction. Other applications include maintenance and personnel training. Nearly all engineering endeavors involve some model effort. In fact, many engineering accomplishments survive only as models—long after the full-scale version has passed into oblivion.

In the chemical industry the engineering process model has become an essential part of engineering design [1-7], as well as being useful in construction[8], maintenance [9,10], and process analysis [11,12]. The model-building itself can be a critical path activity in project engineering [6]. Even the computer design of piping systems can be based on model measurements [7]. Numerous illustrations of such chemical [13] and nuclear [14] plant models can be found in the literature.

This study suggests that the design and construction of process models can serve as an effective introduction to complex design for engineering freshmen.

BACKGROUND

FOR SEVERAL YEARS the engineering curriculum at Clarkson College of Technology has included a two-course freshman engineering sequence. The principal objective of this sequence is to provide an introduction to computer programming and engineering design. The general organization and history of the sequence have been discussed earlier [15,16]. In particular, the second course, entitled “Introduction to Complex Design,” extends throughout an entire fifteen-week semester. During this period, the student is primarily involved in a group design project.

Faculty members from all engineering departments are assigned to this design course as project supervisors. In addition to the faculty instructor, several undergraduate students are usually selected as student tutors for a project and are given an honorarium for this activity. Each instructor for this design course prepares a short project description for distribution to prospective students and from 30 to 70 freshmen are then assigned to a project on a preference-ranked basis. As a result, a chemical engineering project will usually involve students from other engineering disciplines.

There is no fixed format or content for this freshman design course. The only expressed goal is the involvement of the student in some phase of engineering design, preferably through a first-hand experience. As a result, the nature of the course has varied widely [17]. The most effective chemical engineering activities for these large project groups can be classified as design synthesis or design execution.

In the design synthesis approach [18], a loosely-defined process engineering problem is posed. The students, in three-man design teams, are gently guided through the steps of problem definition, flow charting, material and energy balance calculations, equipment selection, and economic analysis as needed to complete a preliminary design feasibility report. Typical projects have involved wet combustion of sewage, conversion of waste to oil, coal gasification, and heat exchanger parameter optimization. This approach is relatively effective for the large student groups involved and is economical to operate. It can easily be guided to completion so as to provide the students with a sense of accomplishment.

The design execution approach has emphasized the planning, construction, and testing of a de-
sign. The student, again as part of a three-man group, actually constructs a prototype design. Typical projects of this type have involved a fuel-cell parameter optimization, fuel-cell power system for a minibike, a hydrogen combustion engine, and a fermentation reactor optimization. Since a freshman engineering student at Clarkson College is not required to take any laboratory courses, this second approach offers the appeal of "gadgeteering" and hardware involvement that many engineering students seek. However, it is more costly and involves an extensive faculty effort to achieve enough hardware development for student satisfaction.

A third approach—process model-building—has now been developed to introduce engineering freshmen to complex design and project engineering.

INITIAL EFFORT

This model-building approach was motivated by student responses on a survey questionnaire during the first class meeting in Spring 1974. The thirty-four students who had selected the project topic "Nuclear Power" expressed a surprisingly strong preference for building scale models of nuclear power plants over a variety of other analytical and laboratory choices. Two independent model-building sections of seventeen students each were rather hurriedly established without much prior planning. Two student tutors were assigned to one section and one to the other. Both sections were under the supervision of a single faculty member. At the second meeting of the class, the guidelines of Table I were developed after some amount of discussion.

During the next four class meetings, sixty-minute lectures were scheduled on the following topics:

- Nuclear Power History
- Nuclear Power Industry-Today
- Reactor Plant Descriptions (PWR, BWR, HTGR)
- Project Engineering (Organization, Schedule, Design and Construction)

Textbook and journal references were provided to stimulate a literature search, reading, and discussion. In addition, the multi-volumed "Preliminary Safety Analysis Review" (PSAR) and "Supplement to the Safety Evaluation Report" (SSER) of both the Diablo Canyon I and Nine-Mile Point I reactor plants were made available. Reasonably thorough system descriptions of the BWR and PWR plants (by General Electric and Westinghouse) were also provided.

The remaining time during the first five weeks was largely spent in student discussions on what to build, where to get suitable information, and how to proceed. The projects were identified as the "Diablo Canyon I Power Plant" and the "Oconee I Reactor Building." These choices appear to have been based on the large amount of PSAR information in the first case and on the availability of a good journal feature story in the second case. The first project quickly named a manager and started to develop as a project team. The other project never selected a manager and tended to operate as independent sub-system groups. At the beginning of the sixth week, the student tutors were encouraged to take a more active role in helping the students develop better project organizations.

From this point on, the Diablo Canyon section quickly evolved into a coherent project group. These students made effective of the many engineering drawings in the Diablo Canyon PSAR. They were able to analyze and interpret the drawings, even to the point of finding two inconsistencies in the drawings. However, the actual model construction was very slow. This can be attributed to the lack of experience characteristic of these students. During the entire semester the students maintained a high level of interest and activity. This produced the Diablo Canyon plant model shown in Figure 1. This section also prepared a well-written report and made an effective oral presentation.

The Oconee section never really managed to develop an overall project organization. However,
the various sub-groups proved to be quite competent at developing drawings and constructing models. This section required considerable direct help from the student tutor. A final crash effort produced the Oconee Reactor Building model shown in Figure 2.

The overall effort, interest, and accomplishment of the two sections were better than had been anticipated. The quality of the models was high enough to utilize them as instructional aids in upper-level engineering courses and as displays. On the negative side, a few students were bothered by the amount of shop or craft work, which they felt was a waste of time. Several students were never really able to adapt to the demands of a group effort and, as a result, lost the sense of participation in the overall project. However, the most severe problem was the lack of prior planning for this venture by the faculty supervisor. This, coupled with a lack of experience for the activity, led to an excessive emphasis on “fire-fighting” activities instead of planned guidance.

SECOND EFFORT

THE NUCLEAR MODEL-BUILDING activity was repeated with a group of 37 freshmen in Spring 1976. Four project teams were organized and an undergraduate tutor was assigned to each. A number of significant changes were made in order to accelerate the initial effort and to introduce the students to project engineering.

The first change was the addition of three more guidelines. The project schedule mentioned in Item 2 was a typical manhours schedule for the entire project. Scheduled manhours for future activities were shown for the appropriate dates and actual manhours for past activities were listed where expended.

At the first class meeting the students were asked to organize themselves into four independent project groups. Source material from reactor plant vendors, utilities, and government agencies were made available and other literature sources were listed. The students were asked to select a project and define the model scope by the end of the second week. This definitely improved the student effort during the first part of the course.

The lectures given to the class in 1974 were repeated, but were spread out in short segments over the first six weeks of the course. In addition, specialized mini-lectures were given in response to requests from the individual project groups. This permitted the groups to schedule a faculty lecture at their convenience and to request specialized topics relating to their particular project.

The four projects of this second effort were (A) Pickering Reactor Building, (B) Fulton Generating Station, (C) Diablo Canyon Reactor Building, and (D) Gentilly II Generating Station. The results, represent a significantly higher level of accomplishment than before. This improved performance probably can be attributed to better planning and organization of the course. The significant factors were (a) better development of the tutors as project consultants, (b) acceleration of the initial project phases, and (c) the requirement of weekly progress reports.

FUTURE EFFORTS

THE DEVELOPMENT OF additional project management techniques for this model-building effort might be effective in generating student interest and providing an introduction to such methodology. Computer programs could be prepared to provide the printouts and graphs.
characteristic of the methods used in project management practice. Using these, the students could prepare schedules, control costs, allocate effort, and develop a better sense of ongoing project management. This would help to illustrate the use of the computer as a managerial tool. It would add realism to the project management task and provide a meaningful management assignment for the students who dislike the shop construction activities.

A freshman-level textbook could be developed for model-building courses. While model-building references exist (19,20) and specialized supply sources are available (21), a need exists for a student textbook covering (a) the specialized techniques of engineering model-building, (b) descriptions of chemical process equipment and their function, and (c) an introduction to project management techniques. This should include numerous illustrations and examples, as well as sample management programs.

PRELIMINARY PREPARATION

A S NOTED ABOVE, the preliminary planning for this course is particularly important. A set of project guidelines should be formulated before the course begins. Those given in Tables I and II evolved from the problems encountered in the initial effort. Other items that should be considered include:

- Adequately documented reference materials, particularly in the form of drawings and photographs, should be assembled for several different projects so as to simplify the design choice, minimize literature searching, and help give the sections an early sense of direction.
- Laboratory areas with sufficient space, work tables, storage cabinets, and tools should be set up for this activity. It is important that each project have a separate defined area. This can be achieved if a “model-table” and related space are assigned to each project group. Additional nearby space should be available for project conferences, writing, drawing, and minilectures.
- A clear definition of the role of the student tutor should be developed. Without this, it is possible for the tutor to assume conflicting roles as instructor, faculty assistant, consultant, project manager, or freshman colleague. A proper balance must be established between guidance and assistance in both faculty-tutor and tutor-freshmen relationships.
- Project conferences and mini-lectures should be planned to introduce the unit operations and chemical processes associated with the prototype. This helps to focus attention on the fullscale prototype as a functional unit.
- Some instructional effort should be devoted to the concept that model-detailing is the art of creating an illusion of reality, rather than true prototype miniaturization. When student effort seems to be misguided, it is particularly effective to offer one possible solution and challenge the project team to seek other solutions.

DISCUSSION

A S AN INTRODUCTION to complex engineering design, this model-building approach provides an outlet for the creativity, curiosity, and ingenuity that characterize many engineering freshmen. Even though miniaturized, it tends to focus upon the total art of engineering design [22] through practice in a real-world environment.

The student is not involved in analytical design or actual equipment operation, as he would be in the other types of chemical engineering projects mentioned earlier. However, he is introduced to the techniques and needs of project engineering, as well as learning to function as part of a large project team. It is also possible to use this model-building project to acquaint the student with the appearance, purpose, and function of process equipment used in the prototype.

The faculty supervisor can utilize the modeled process as a vehicle around which to develop problems in upper-level engineering courses. One possibility is to have the freshmen model a project that is being studied concurrently by a senior design group. Another approach is to utilize area industry as prototypes and include plant tours as part of the course. Incidentally, a faculty member can even generate interest in his research specialty by developing a model project that relates in some way to his research.

From an administrative point of view, this model-building approach should be of interest because (a) it can be made appealing to a wide variety of engineering students of all disciplines, (b) a reasonably large number of students can be accommodated effectively and economically, and (c) it involves the freshman student with a real design experience that can be satisfactorily completed in a fixed time schedule. This type of course could even be offered to non-engineering freshman as an introduction to engineering.

The student tutors, who usually are juniors and seniors, can gain an invaluable educational experience by working with a process model-building group. This is particularly true if they are given considerable responsibility for helping the freshmen develop an effective project organization and complete the project on schedule.

Continued on page 151.
RANKING CHEMICAL ENGINEERING DEPARTMENTS

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THIRTY YEARS AGO it was a relatively simple task for those in industry, government, and education to rank or rate chemical engineering graduate programs. At that time, programs were few in number and could be easily evaluated by knowledgeable observers. The trends of the intervening years, namely, the rapid proliferation of graduate programs and the general rise in quality have clouded the situation. In the complexities of today's academic world, the simplistic insights of the past no longer work. It is essential, therefore, to have realistic, objective techniques for graduate program evaluation.

Others have grappled with this problem [1], [2], [5]. For example, in 1966 the American Council on Education (ACE) published the

The ACE Studies . . . depended to a large extent on opinion. As such there was always the question of personal subjectivity or in some cases the danger of lack of knowledgeability. . . . lesser known departments could be ignored because they do not have the national exposure of better known units.

The Cartter Report “An Assessment of Quality in Graduate Education” [1]. Again, in 1969 the same organization completed a follow-up study “A Rating of Graduate Programs” by Roose and Andersen [2]. Basically these studies consisted of polling selected faculty members in universities and asking them to rank departments both on “quality of Graduate Faculty” and “Effectiveness of Doctoral Program.” The initial study by Cartter found a high degree of correlation between these rankings. This was in essence replicated in the 1970 study. The results of these studies for chemical engineering departments are given in Table I.

<table>
<thead>
<tr>
<th>School</th>
<th>1966</th>
<th>1970</th>
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<tbody>
<tr>
<td>Wisconsin</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Minnesota</td>
<td>4</td>
<td>2</td>
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<tr>
<td>Cal., Berkeley</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>M. I. T.</td>
<td>1</td>
<td>4</td>
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<tr>
<td>Stanford</td>
<td>10</td>
<td>4</td>
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<tr>
<td>Illinois</td>
<td>8</td>
<td>6</td>
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<tr>
<td>Princeton</td>
<td>3</td>
<td>6</td>
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<tr>
<td>Michigan</td>
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<tr>
<td>Cal. Tech.</td>
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</tr>
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<td>Delaware</td>
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<tr>
<td>Northwestern</td>
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<tr>
<td>Rice</td>
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<td>13</td>
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<tr>
<td>Carnegie-Mellon</td>
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<tr>
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<td>—</td>
<td>15</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Wash. (Seattle)</td>
<td>—</td>
<td>17</td>
</tr>
</tbody>
</table>

The ACE studies, while valuable, depended to a large extent on opinion. As such, there was always the question of personal subjectivity or in some cases the danger of lack of knowledgeability.
For example, lesser known departments, although capable, could be ignored because they do not have the national exposure of better known units. The present paper develops a system whereby objectivity can be maximized and the potential problems of the earlier studies can be avoided.

INDICES OF PERFORMANCE

The methodology used in this study is simple, direct, and effective since it is based on published statistical data. Fundamentally, rankings on four indices of performance are used to generate an overall index of performance that ranks chemical engineering departments by effectiveness or productivity. Unlike the earlier studies, this ranking reflects overall graduate and research productivity and not just doctoral program effectiveness. The four indices of performance are: Master's Degrees Awarded per Faculty Member per Year, Doctoral Degrees Awarded per Faculty Member per Year, Thousands of Dollars of Extramural Research Funds Expended per Faculty Member per Year and Refereed Publications per Faculty Member per Year.

The development of indices based on units of performance per faculty member was purposeful. First, it was felt that gross data such as numbers of M.S., Doctorates, or publications for a given department could be quite misleading. For example, a small department (of say five faculty) could turn out five doctorates and appear not as productive as a large department (of say twenty faculty) that turned out ten doctorates. Yet, if these data were reduced to the basis of per faculty member, the smaller department would have an index of 1.0 while the larger department would be only 0.5. Thus, a clearer, more objective picture could be obtained.

Two sources of information were used for the statistical data to compute the indices. The first was the annual supplement of Engineering Education titled, Engineering College Research and Graduate Study [3]. This volume gave the numbers of Master's and Doctor's degrees awarded and the amount of extramural funds expended. The American Chemical Society publication [4], Directory of Graduate Research, furnished listings of refereed publications. The former source [3] gives annual data while the latter is on a biennial basis.

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The National Academy of Science appointed him as Senior Visiting Scientist to Poland in 1971. In the same year he was appointed Dean of the College of Engineering and Applied Science of the University of Wisconsin-Milwaukee as well as Professor of Energetics.

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... in this study ... rankings on four indices of performance are used to generate an overall index of performance that ranks chemical engineering departments by effectiveness or productivity. Unlike earlier studies, this ranking reflects overall graduate and research productivity and not just doctoral program effectiveness.

Frequency distribution plots of index values for all four categories are given in Figures 1, 2, 3, and 4. These data give a valuable insight into the performance of chemical engineering departments. If the most frequent index is taken for all four areas, the performance of an "average" department could be computed regardless of size of faculty. For example, such a ten member department would generate 7 M.S. degrees per year, 3 doctorates per year, $170,000 in total extramural research funds per year and 14 total refereed publications per year. On the other hand, a twenty member department would double those figures for "average" performance.

DECIMAL SCALE APPROACH

Although such data as Figures 1-4 are useful, they do not answer the question of overall effectiveness or productivity. In order to satisfy the need, a different approach was taken. This approach involved the reduction of the indices in each area to a decimal scale. For example, consider the situation for Master's degrees per faculty member per year. The top value determined for any institution was 2.08. This figure was then divided into each index value to give a reduced decimal score (i.e. $\frac{2.08}{2.08} = 1.00; \frac{1.04}{2.08} = 0.5$, etc.).

The same process was repeated for the other three areas (of course, using the appropriate top index value). The result was that each area now could be described on a decimal scale ranging from low values to unity. The top index values for all four areas are given in Table II.

Next, the reduced decimal scores for the four areas (i.e. Master's Degrees per Faculty Member per Year, etc.) were summed for each chemical engineering department for which all four categories were available. Theoretically, the top score would be 4.00. Actually, this value was found to be 2.75. This figure was then used to reduce all the data to a decimal score (i.e. $\frac{2.75}{2.75} = 1.0$). These decimal scores were designated as a Graduate and Research Productivity Index (GRPI). The final ranking of the institutions by means of GRPI is given in Table III.

Institutions that were used in the various phases but not in the final compilation (because of lack of certain data) are given in Table IV. Before commenting on the data of Table III, it is worthwhile to cite the fact that one of the institutions of Table IV had the top index in the area of publication. However, none of the others were at the top of the remaining categories.

Now, in regard to Table III, the rankings were listed as shown to match the system used by
Cartter [1] and Roose and Andersen [2] in their earlier studies. In essence, first a ranking of schools by order in the higher category and second an alphabetical listing of the other institutions that ranked lower. As a first step, it was decided that correlation between each of the earlier studies and the present should be checked. It was found that the respective correlation coefficients between the present work and the earlier studies were 0.5 for the Cartter Report and 0.73 for the later study by Roose and Andersen. The probability levels for correlation were about 0.10 for the Cartter Report and between 0.01 and 0.001 for the later study. The greatly improved correlation with the Roose-Andersen study most likely reflects changes in departmental effectiveness with time. The interesting result of the correlation is that there is a strong relation between the perceptions of the faculty raters and the objective rating system used in this work for the top rated institutions.

As was indicated, the earlier studies only ranked numerically the top rated institutions. The groups following these were cited only alphabetically. This, of course, prevented a direct correlation study being made of all listed schools. However, it was possible to make an indirect check. This was done in the following manner: the names of the first 37 institutions in the present study were compared to those named in Cartter's work [1] (i.e. Cartter listed 39 departments, two of which no longer exist) and the names of the first 55 institutions in the present work were compared to the 55 listed by Roose-Andersen [2]. The number in common was then divided by either 39 or 55 as the case dictated. The result was about a 60\% ratio. Furthermore, if the departments not included in the present study because of lack of complete data were dropped, the ratio ran up to the 90\% level.

As a result of the direct correlation and the indirect approach it can be seen that the results from the faculty panels used earlier compare quite favorably with the present objective technique. This shows that the perceptions of knowledgeable faculty are a good guide to qualitatively ranking departmental effectiveness. However, it should also be apparent that the objective technique set forth in this paper gives a one to one quantitative ranking of departmental productivity or effectiveness which should be more meaningful.

It is interesting also to consider the findings of Bernier, Gill and Hunt [5]. These authors correlated a number of factors (citations, research expenditures, publications, etc.) for 21 ChE departments named in the Roose-Anderson study [2]. They found good correlation between various factors dealing with citations and research expenditures and the Roose-Anderson work [2].
Institutions Not Rated But Used To Supply Certain Data

A. The following institutions were used to supply data for the evaluation of M. S. doctorate and extramural funding.

<table>
<thead>
<tr>
<th>Institution</th>
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<tr>
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<td>Arizona</td>
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<td>Michigan Tech.</td>
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<td>New Mexico State</td>
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<td>Tulane</td>
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<td>Tulsa</td>
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<tr>
<td>Washington State</td>
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<tr>
<td>Washington (Seattle)</td>
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<tr>
<td>Wyoming</td>
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</tbody>
</table>

B. The following institutions were used to supply data on doctorates and publications.

<table>
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<td>Syracuse</td>
</tr>
<tr>
<td>Texas A &amp; M*</td>
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<tr>
<td>Yale</td>
</tr>
</tbody>
</table>

*Also involved in M. S. Evaluation

The question that naturally arises is what about those institutions in Table IV or others for which no data were available? This can be handled by first pointing out what was cited earlier, namely, that all available data were used to compile the decimal scores that were summed to get the GRPI. In fact, as was mentioned earlier, the 1.0 decimal score for publications was attained by one of the departments in Table IV. Actually there is no problem in any department finding where it ranks by this method. In Figure 5, the ranking corresponding to this GRPI shows that the institution ranks above 88% of the institutions or that only 12% of the institutions rank above it.

CONCLUSIONS

It is felt that the method outlined in this paper offers an objective realistic way of evaluating chemical engineering department graduate and research productivity and effectiveness. In light of the excellent correlation between “Quality of Graduate Faculty” and “Effectiveness of Graduate Programs” found by both the Cartter and Roose-Andersen studies, it would also appear that the scale developed in this paper also is a strong indicator of quality of graduate faculty in chemical engineering departments. Beyond the apparent impact on rank, there is another important ancillary benefit. This is to provide chemical engineering departments a way of comparing their annual performance on a year by year basis. In other words, is the department standing still, declining or improving? In today’s tight academic budget situation, the method presented in this paper could be extremely useful in showing reluctant university administrations that a given program is either worthwhile or on the upgrade. Regardless, however, of the ultimate use to which the present method is directed, it cannot but help to bring a more reasoned approach to an important area of consideration.

REFERENCES

university research administrators. He prepared a proposal for submission to NSF without the usual overhead funds in the budget. The document managed to clear all but the Treasurer’s Office. When news of the attempt filtered back like a water hammer, there were an awful lot of red faces, but not Jim’s.

DOUGLAS AS ENTREPRENEUR

ONE ROLE AN ENGINEER often plays is that of an entrepreneur. An outgrowth of Douglas’s interest in sailing brought him into partnership with two other engineers from U. Mass., seeking to develop new metal forming procedures useful in forming hulls. His avocation energized an interest in Engineering Entrepreneurship and developed course material for both undergraduate and graduate courses.

We began this article with a clear exposition that James M. Douglas is an uncommon man. This we have shown as true in all his pursuits of scholarship and of leisure. His intensity fires the interest of students and of some colleagues, and the passions of others. “L’éménence grise” (for the gray hair) continues to be a major contributor to the growth of this department and the chemical engineering profession.

ALKIRE: The ChE Profession

Continued from page 129.

course described here achieves its purpose in an efficient manner.

REFERENCES


WILLIAMS & COSART: Freshman Analysis

Continued from page 135.

has been enthusiastic. We feel that they have a much better understanding of chemical engineering and are certainly much better equipped to handle a rigorous stoichiometry course in the next semester as a result.

REFERENCES


ChE news

WORCESTER, Mass.—Dr. Imre Zwiebel has been appointed head of the Worcester Polytechnic Institute chemical engineering department, effective Sept. 1.

He has been a member of the WPI faculty since January, 1964, when he came to Worcester after three and a half years as a research and development engineer with Esso Research and Engineering Co., Linden, N.J.

A native of Budapest, Hungary, he came to this country in 1948 and was educated in New York City. Following graduation from University of Michigan with a bachelor of science degree in chemical engineering, he was employed for three years by E.I. DuPont Demours & Co. in Wilmington, Delaware.

He held four fellowships at Yale University where he received both Master of Science and Doctor of Philosophy degrees.

SUMMER 1976
THE PRACTICE OF ENGINEERING, like the natural sciences, involves many quantitative relationships and operations. Hence, education in this field includes many, hopefully realistic, exercises using these relationships. These exercises generally take the form of problems intended to illustrate or reinforce a given concept, and are used as homework assignments, lecture demonstrations and examination topics. There are many areas in chemical engineering, including reaction engineering, in which quantitative problems are employed more or less extensively in the educational process.

The instructor of ChE, particularly one who specializes in a given field such as reaction engineering and who regularly teaches in this field, rapidly accumulates a copious set of quantitative problems for the purposes mentioned above. After some time, the organization and management of these resources can become an unwieldy and frustrating task. In particular, the operation of information retrieval, as it applies to the act of selecting a problem for the purpose of illustrating a given concept, often requires more than just a good memory (especially if some variety is hoped for in course offerings). Thus, the purpose of this article is to describe an efficient manual method for organizing reaction engineering problems, the list of identifying concepts can be kept to a size easily manageable by manual methods. As an aside, the very act of organizing the subject matter of a given field into such key concepts is, by itself, a very valuable aid in the structuring of a course into modular units.

The usage of the key concept method for information retrieval has been described by numerous authors (1-4). After the key concept words for a given application have been selected, a table form, typically an index card, is set up for each such key concept. Items to be accessed via this system are then assigned code numbers which are essentially arbitrary; the only restriction is that there be a one-to-one correspondence between each item and each number. The code number for a given item is then recorded on the table forms for each of the key concepts associated with or imputed to this item. For a manual system the code numbers are generally arranged in an ascending order for each key concept; typically, larger numbers are assigned as the system grows. A separate reference file is maintained which relates each code number to its item. When the items being organized are literature articles in some scientific field, for example, the reference file might consist of another set of index cards, arranged in ascending numerical order with one code number per card, with such pertinent information as author(s), affiliation, source, abstract and the...
The system then operates as follows for the retrieval of specific items. The table forms or index cards for each key concept of interest in a given search are scanned and all code numbers which appear on all such table forms are stored or recorded. The code numbers resulting from this scanning operation are then used to locate the corresponding items (journal articles, abstracts, etc) in the reference file. In very sophisticated systems, additional letter or numerical codes may be assigned to each key concept. The purpose of these additional codes is to denote the role of each key concept. Thus, these codes may be used to denote whether the key concept serves as an input, output, environmental factor, active concept, passive concept, means, etc. These role codes can then be linked to establish a very specific search of a large system. In this case, a given key concept may require a number of separate table forms, one for each role code assigned to that word. In a relatively simple system such as the one described in this article, such sophistication is not necessary and was not employed.

The list of key concepts selected for this reaction engineering application is given in Table 1. It is not pretended that this list would serve as an all-inclusive one for the entire reaction engineering field. Within an educational environment, however, it is felt that this list is quite representative of the key concepts covered in a typical undergraduate course in chemical reaction engineering. The reference file for this problem organization system would relate each code number to a specific problem or the source thereof. In the search operation, code numbers would, as before, be obtained by scanning and recording the matches. A specific example of this search procedure will be given later.

The selection of the key concepts themselves is naturally somewhat subjective. A given person may attach various subtle interpretations to certain key concepts. Hence, amplification of some of the entries in Table 1 would perhaps be useful. For example, numerical integration is intended to refer to problems in which analytical integration of the governing differential equations is not possible, and would thus also embrace graphical and other manual methods of integration. The nonisothermal entry is intended to also include series of reactors operated at different but perhaps constant temperatures. A key concept such as activation energy, half-life, residence time or selectivity is associated with a given problem only when that concept is felt to be an integral part of the solution procedure to that problem.

The items to be organized in this system are problems in the area of reaction engineering from various sources such as textbooks, manuals and journal articles. The problems from textbooks can be either solved example problems or unsolved ones such as appear at the ends of various chapters. For brevity of presentation purposes in this article, the number of organized problems has been restricted to several hundred, but the extension of this system to any number of entries should be readily apparent.

Copies of the table forms for this system are shown in Table 2. This particular type of form, with a vertical arrangement into ten columns headed by the digits 0-9, is a very popular one. The code number for a given item is listed in one of these columns, depending upon its last digit. Within a given column, the code numbers are listed vertically in ascending order. This particular arrangement of the code numbers on a table form greatly facilitates the search procedure. The code numbers for individual reaction engineering problems beginning with unity, are assigned in ascending order as the number of entries increases and are recorded manually on the appropriate table forms.

The reference file for this system is presented in Table 3. A shortcut, mnemonic method for identifying sources has been employed here. This method, although somewhat arbitrary, has proven
MULTIPLE REACTORS

NON-ISOTHERMAL NUMERICAL INTEGRATION

TABLE 2
The usage of this system for locating problems involves specific concepts will be illustrated by two examples. Suppose one is interested in referring to the text by A. R. Cooper and G. V. Jeffreys. The numbers following the author letter codes denote the location within a given text. Again, for example, 3-4 refers to problem 4 at the end of Chapter 3, while 157X refers to an example problem which appears on page 157. A complete directory of the mnemonic codes is provided in Table 4.

### TABLE 3. Reference File Code Numbers and Sources of Reaction Engineering Problems.

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<td>41 C&amp;J 5-7</td>
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<td>SMW 4-26</td>
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<td>42 C&amp;J 5-8</td>
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<td>OL2 7-41</td>
<td>SMW 4-28</td>
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<td>OL2 7-42</td>
<td>SMW 4-29</td>
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<td>45 JMS2 79X</td>
<td>JMS2 4-31</td>
<td>JMS2 5-29</td>
<td>OL2 5-34</td>
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<td>JMS2 4-32</td>
<td>JMS2 5-30</td>
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<td>OL2 7-44</td>
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<td>47 JMS2 2-3</td>
<td>JMS2 4-33</td>
<td>JMS2 5-31</td>
<td>OL2 5-36</td>
<td>OL2 7-45</td>
<td>SMW 4-32</td>
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</table>
action engineering problems having to do with consecutive, competitive, second-order reactions occurring in a CSTR. A scanning search of the table forms for each of the four key concepts associated with this class of problems discloses that the following code numbers appear on each of these forms: 93, 193, 195, 196, 98, 99. Similarly, a search for problems involving reaction mechanisms leading to fractional reaction orders yields the following entries common to each of the two pertinent table forms: 251, 252, 253, 47, 249. Some suggestions regarding the usage of these forms are presented below.

Large numbers of organized items (problems) necessarily appear on the table forms for the more general key concepts, such as first-order, second-order, batch, tubular and CSTR. In a given search involving several key concepts then, one is well advised to first scan the table forms for the more specialized pertinent concepts, e.g., autocatalytic, half-mile, multiple reactors, and then to proceed to the more general concepts. This sequence prevents the initial accumulation of a large number of item code numbers which would later have to be discarded.

This article has described the usage of the key concept method of information organization and retrieval for setting up and organizing a

<table>
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<th>CODE</th>
<th>SOURCE</th>
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<tr>
<td>AIChE</td>
<td>“Chemical Engineering Problems,” American Institute of Chemical Engineers, New York (1956) (K suffixed to associated numerical codes refers to the problem set on reaction kinetics).</td>
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</table>
file of reaction engineering problems. This file, which has been organized and maintained by manual methods with no great effort, has been found to be very useful in an educational environment. It should be obvious, moreover, that these same methods should be amenable to other instructional areas of chemical engineering. Thus, one should be easily able to construct similar files, if one is interested, for such areas as thermodynamics, unit operations and process control, to name a few.

REFERENCES


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than precise. Professor Astarita attempts to explain the methods in a setting which anticipates the heavy technical needs of the final chapters on fading memory, a strategy which I think taints his exposition of fundamentals with a vagueness impossible to avoid in such an ambitious undertaking.

For example, I believe Chapter 4 is seriously flawed by its opening section which, in anticipation of Chapter 5, deals with differentiability of functionals with respect to present values of temperature. This discussion is too vague to be of much use, plays no real role in the balance of the chapter, and is likely to detract from the effectiveness of the pedagogically critical sections immediately following. I wish Professor Astarita had chosen to divorce his exposition of methodology from his skillful, but necessarily sketchy, description of Coleman's work on fading memory.

I wish also that literature citations had been heavier so that readers could more readily make contact with the original literature—indeed, the crucial Coleman-Noll paper of 1963 is not cited at all.

Despite these remarks, let me state once again that the book is an important one for academic chemical engineers and might substantially influence the way we think about thermodynamics. It deserves reading, as do the source papers and the monographs by Truesdell and Day. Professor Astarita has reached beyond our own literature and brought to it something of value.

REFERENCES


WARD: Process Model-Building
Continued from page 139.

ACKNOWLEDGMENT

Financial assistance from Combustion Engineering helped make these projects more effective than they might otherwise have been.

REFERENCES


LETTERS: Carberry
Continued from page 107.

How, for example, in the name of God, Zeus or whatever deity prevails in Buffalo, is Yale* placed in the tail end “of the class” relative to Buffalo? How is it that Yale University is ranked with Judas in the Gill report when, in fact, an even casual survey of their research endeavors would prompt even a Big-8 anti-Ivy league-type to conclude that the graduate research-study program at Yale is vastly more fundamentally significant than that of one-half of those departments blessed with top 20 categorization by Gill et al.? How is it that perhaps several of the departments assigned a rank in the top twenty by Gill et al. (including, oddly I contend, his university) would, on survey, be totally innocent of the nature of Yale’s labs and the Journals within which the Yale Chemical Engineering people deposit their findings?

I leave it as an exercise to Gill enthusiasts to seek out those non-AICChE Journals in which Yale Chemical Engineering people choose to publish their research findings, which areas they choose to pursue as ultimately relevant to the science of chemical engineering.

We, in chemical engineering, have gone well beyond the usual pedestrian levels of research inquiry. Survey your colleagues, dear reader: where do they publish? Perhaps in an AICChE publication; perhaps elsewhere. Our noble calling has become, happily, diffuse insofar as borderlines between chemical engineering and chemical physics are no longer clear and well defined interfaces. This I welcome. Provost Gill’s survey respects not this reality.

Yale has been and is and will always be a great university, a summation of innovative departments of distinct, unique insight whether in the area of literature or chemical engineering. Having had a distinguished department of traditional chemical engineering for enough decades to even inspire a Buffalo, they now choose to pursue a program of education and research in the chemical engineering sciences, which enterprise might ultimately enlighten over-inflated Buffalo.

As this comment is quite personal, permit me to fashion the “Carberry Report”—an evaluation of graduate chemical engineering departments in two categories: general (catholic-note, please, the lower case c) and specialized (I leave it to reformation theologians to fashion a more definitive category):

**General:**

1. Minnesota
2. Delaware
3. Berkeley
5. Illinois
6. Northwestern

**Specialized:**

1. Stanford
2. Yale
3. Princeton
4. Pennsylvania
5. Wisconsin
6. Everyman’s School

Beyond that, my friends and enemies, its “to each his own.” As for the unmentioned, do your own grand thing. The “Carberry Report” respects all who labor in the vineyard, even Gill’s Buffalo.

U. of Notre Dame
J. J. Carberry

*of which I am proud to be an alumnus.

CHEMICAL ENGINEERING EDUCATION
Is the leg mightier than the atom?

Before you say no, keep in mind that we know very little about many forms of energy available to us.
Including good old muscle power.
For too long a time we’ve relied on oil and gas to serve our needs, and failed to take full advantage of other sources of power.
Including the atom.
But recent events make it clear we must learn about all the options, and how best to apply them.
At Union Carbide we’re studying a wide range of energy technologies and resources for the Energy Research and Development Administration.
From something as basic as bicycling to the complexity of controlling nuclear fusion.
For instance, we are learning how to turn coal into oil and gas in a way that is practical economically.
We’re deeply involved in nuclear research, particularly in finding ways to make this important source of energy safer and more efficient.
Our work in fusion power, at Oak Ridge, Tennessee, offers the most exciting possibility for the future: the ultimate source of inexhaustible energy.
If we succeed, there will never be another energy crisis.
But for the present, the answer to our energy dilemma is not likely to come from one source, but many. All the way from the leg to the atom.

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We're looking for people who are looking for the good life. The good life involves a lot of the things we've always taken for granted. Like the availability of enough food to feed an ever-growing population. A cure for disease. Thick forests. A clean environment. And the time to relax and enjoy it all. Except now we're going to have to stop looking at life through a tunnel and find ways to protect all forms of it—from our homes to the farthest corner of the earth. Because life is fragile. And its protection is a major concern at Dow. So we're looking for people with scientific, engineering, manufacturing and marketing backgrounds who'll direct their precious talents, enthusiasm and ideas to the development of Dow products and systems for the good life. And we'll provide a dignified, motivational environment to work and grow. If you or someone you know loves life and wants to live it wisely, get in touch with us. Recruiting and College Relations, P.O. Box 1713, Midland, Michigan 48640.

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