CEE

chemical engineering education

VOLUME XVI • NUMBER 1 • WINTER 1982

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

SPECIAL DESIGN ISSUE

• *Award Lecture* •

DESIGN RESEARCH . . . BOTH THEORY AND STRATEGY

Arthur W. Westerberg

JOE MARTIN

of Michigan

also

• *CHE AT CINCINNATI* •

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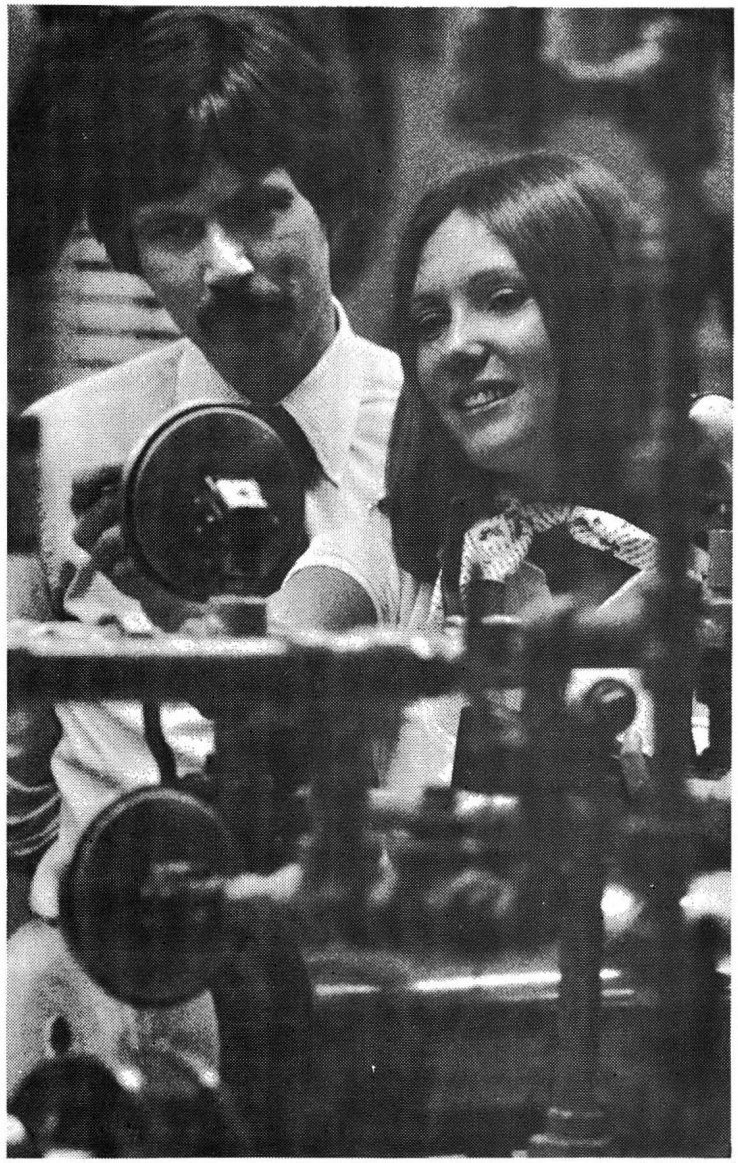

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Chemical Engineering Education

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ChE educator

Joe Martin of Michigan

... Professor and Professional ...

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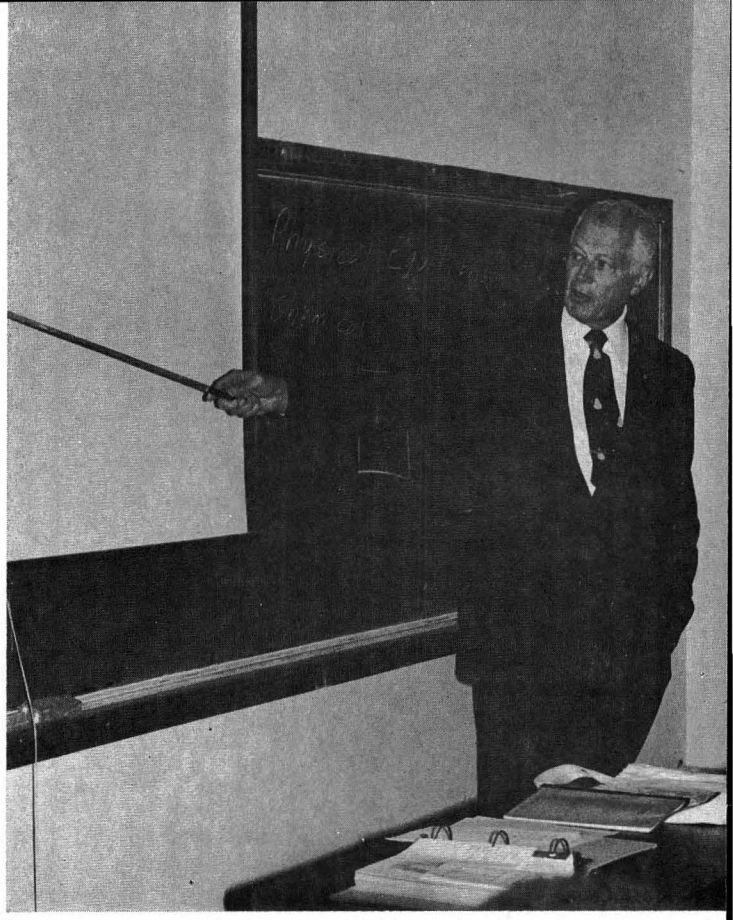


JOSEPH J. MARTIN has established himself as one of the best known and universally admired faculty members in chemical engineering. He received his B.S. from Iowa State University in 1939, and worked with the Eastman Kodak Company for the next two years. Subsequently, he was awarded an M.S. from the University of Rochester in 1944, and obtained his D.Sc. from Carnegie Mellon University in 1948; he was an instructor in chemical engineering at both of these institutions. Coming to the Department of Chemical Engineering at the University of Michigan in 1947 as an Assistant Professor, he was promoted to Professor in 1956, and has also held a joint appointment as Associate Director of the Institute of Science and Technology since 1965.

Joe Martin's contributions to chemical engineering have been so pervasive and extensive over the last 40 years that few, except for the new generation of chemical engineers, could not be fully aware of their impact. Yet, it has been for the current and future generations of engineers that his efforts have been targeted. Joe has taken on the mission of developing the framework for the maturation of engineering in general, and chemical engineering in particular, into a profession that takes a responsible leadership in the application of technology to societal needs.

He has developed a unique pedagogical approach for teaching thermodynamics in which he prepared a notebook and slide presentation with each of its 200 panels presenting the essentials of one aspect of thermodynamics. This methodology has gained wide acceptance . . .

His has been a multifaceted approach, spanning the dimensions of teaching, research, and professional organizations.

For many of the 3000+ students who have graduated from the Department of Chemical Engineering at the University of Michigan during his tenure on the faculty, his direct influence has been in the classroom and particularly in that abstract and somewhat esoteric field of human invention known as thermodynamics. Joe sees thermodynamics as one of the major intellectual achievements of mankind, in that for all its highly mathematical conceptual basis it concisely summarizes much of the characteristics of the real world. Joe is a master at bringing this realization to undergraduates and graduates alike, along with an ability to apply these principles effectively. He has developed a unique pedagogical approach for teaching thermodynamics in which he prepared a notebook and slide presentation with each of its 200 panels presenting the essentials of one aspect of thermodynamics. This methodology has gained wide acceptance in the chemical engineering community and has been made available by AIChE to large numbers of faculty and students throughout the country. Here, he has combined his insight into the logic of thermodynamics and

his extraordinary ability as a teacher to set forth the various equations and principles of thermodynamics in a clear, concise, and readily assimilated fashion.

Students recognized Professor Martin's gift of teaching effectiveness nearly thirty years ago by giving him the Phi Lambda Upsilon Teaching Award, and this ability has even been enhanced by time. For example, one student recently said, "He is eloquent, not dry and technical. Philosophical interjections provided day-to-day applications and considerations," and another reported "Professor Martin is a very, very excellent teacher in a most difficult course. He explained the tough course matter in a manner which was easy for the student to grasp and like. He made it interesting."

Joe's love and appreciation for thermodynamics has been constant and unwavering over four decades even though the fashionability of the discipline has gone through cycles. Recent world-wide political developments and the realization of the very high economic value of energy has catapulted thermodynamics (or as Joe puts it, the "science of energy") back into the center stage of relevant technology.

Joe and his students have devoted many arduous years obtaining precise thermodynamic data of substances so as to provide the testing ground for the "Holy Grail" of thermodynamics —a General Equation of State. Of his more than 100 publications, nearly a third have been related to this effort. Not one to be distracted when he has decided on a goal or a challenge, Joe has tenaciously battered, chipped, and molded, as a sculptor converts a marble stone into a work of art, to express the refinements and essence of thermodynamics in an aesthetically pleasing equation of state. Much of this effort has been capped in a recent paper with the disarmingly simple title "Cubic Equations of State—Which?" (*IEC Fund. 18,* 81, 1979).

Joe has always coined charming and interesting titles such as his famous "Antidisestablishmentarianism" (*CEP 68,* 19, 1972) and "When Is a Man Half a Horse?" (*CEE 13,* No. 2, 73, 1979).

Always prolific in technical writing, October, 1981, marked his latest publication; a small book sporting a 'maize & blue' cover entitled, "Unified Approach to Series and Integrals of Orthogonal Functions." This is directed in particular toward an advanced study in mathematics.

We would not want to leave the impression that Joe has been single-minded in his pursuit of science. That would omit the other two-thirds of his contributions, which may be overshadowed by his achievement in thermodynamics but in their own right were significant landmarks in other disciplines. For example, recognition of Joe's pioneering work in radiation chemistry led to his election as Chairman of the Division of Nuclear Chemistry and Technology of the American Chemical Society (1962) and also to the Chairmanship of the Nuclear Engineering Division of the AIChE (1962).

Joe Martin with students Michael Longpre, Suzanne Farran and Diane Delonnay.

This high level of achievement in teaching, writing, and research, has provided the base of Joe's other long time commitment—the improvement of the professional status of engineering. Simultaneously with his technical activities, Joe has dedicated himself to service to his profession. He has volunteered his services and energies to professional societies, which when taken together, compromise a "Who's Who" of Engineering. He has been president of AIChE (1971), president of Engineer's Joint Council (1973-75), president of ASEE (1978), and was founder and first chairman of the Association for Cooperation in Engineering (1975-78). It is through the ACE that his goal of a unified voice for engineering is finally coming to fruition. A very visible result of Joe's efforts is this journal, *CEE,* which came into being during Joe's tenure in ASEE. He has

. . . a profession does not exist in a vacuum—but derives its meaning, value, and goals through both its responsiveness to needs of society and its influence on the direction of society. Being an engineer carries with it a serious responsibility which must be met in a considered, thoughtful manner by the engineers who are developing the new technologies . . .

also served on the Engineers Council for Professional Development (1973-80), and is currently chairman of the Education and Accreditation Committee of the AIChE.

He was given an Honorary D.Sc. degree from the University of Nebraska in 1971 and received the Founders Award of the AIChE in 1973.

Why this selfless dedication to his profession? Well, perhaps it is best to quote Joe himself on this—"We have an unusual collection of talent in our memberships, drawn from industry, government, and education, and are capable of directing it in a relevant manner for the best interests of the individual, the specific group, and the nation as a whole. Thus, a profession does not exist in a vacuum—but derives its meaning, value, and goals through both its responsiveness to needs of society and its influence on the direction of society. Being an engineer carries with it a serious responsibility which must be met in a considered, thoughtful manner by the engineers who are developing the new technologies if these advances are to play a positive role in our society." Quoting from his Phillips Lecture entitled, "No Engineer Can Serve Two Masters—or Can He?" "My contention is that more is generally accomplished by bringing people together than by pulling them apart. The intervenors who seek to attain their goals, no matter how worthy, through divisive techniques are far less likely of eventual overall success. Their efforts to pit engineers against their employers are based on an asserted advantage to the public, but this is dubious."

". . . obtaining precise thermodynamic data of substances . . ."

In these times when there has been an awakening of the need for better university/industry cooperation, it is remarkable that Joe has been a catalyst in this area for the last fifteen years. About half of Joe's University appointment during this period has been in the Institute of Science and Technology of the University of Michigan. As Associate Director of IST, (and Acting Director from '78 to '81), he has led an effort to bring industry and university leaders together in conferences, workshops, and study groups. More than twenty-five "state of the art" monographs have resulted, ranging in topics from the highly technical "Data Processing Fundamentals" to the more prosaic "Vacation Housing." Through Professor Martin's work in IST, he has been an integral part of research at the U of M and serves on special committees in the Office of the Vice-President for Research and is a member of the Executive Committee of Macromolecular Research Center.

Those who know Professor Martin well are aware that just as he is synonymous to thermodynamics, so too is he to tennis; he approaches this recreational game with the diligence and aggressiveness mostly accredited to professional tennis players.

Born in Iowa and raised in Omaha, Nebraska, at the young age of 12, Joe acquired his affinity for the sport from his father, Joseph Wesley

Martin, a school teacher and an avid tennis player. Joe took the game seriously and was on the Varsity Tennis Team at the University of Rochester, followed by competitive playing for over 35 years in the Ann Arbor City and University Faculty Tournaments. Having been in the finals many times, as recently as August, 1978, he won the "Ann Arbor Men's Singles—Over 40" title against contenders 22 years his junior. The newspapers aptly dubbed him "King of the Court!"

Although Professor Martin belongs to three tennis clubs, he says he enjoys playing at the University of Michigan Track and Tennis Building "best" because of the "fast-action" of the wood boards.

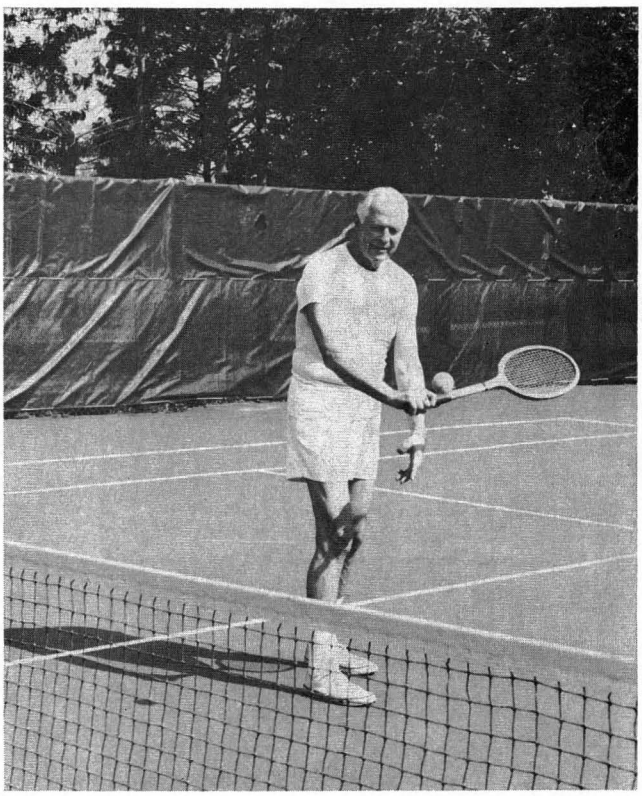
Arriving at the office in East Engineering Building at 7:30 a.m. every morning and always being punctual for classes and meetings, he begins his busy schedule, deftly arranging (sometimes almost surreptitiously) sufficient time in the day —for tennis. Playing with colleagues and students during noon hours, or just practicing on the backboards for an hour or two is an essential part of his day.

An inveterate traveler, logging some 30,000 miles/year during the height of his involvement in society work, he never leaves home without a tennis racquet in hand—nearly always having preplanned a game or two over the phone or by letter before the trip. But if not, he quickly negotiates one when he arrives, since he has "tennis friends" everywhere in the country.

Joe Martin's contributions to chemical engineering have been so pervasive over the past 40 years that few, except for the new generation . . . could not be fully aware of their impact.

Last fall, Joe required surgery to replace his right hip joint. One of his concerns was, "Was this going to bring his playing of the game he loved so much—to an end?" Fortunately that is not the case; now, even though he plays "just doubles," he is back on the courts. A 6′ 4″ charisma-endowed player, agile at 64, and using his great power of concentration, he is still competitive; but most of all "happy" to be playing tennis again, one of his first loves!

Together with the weight and extent of Joe Martin's professional responsibilities, he has involved himself in community service and has been a dedicated family man. Mrs. Martin (Terry) has traveled far and wide with Professor Martin and has always been his strong supporter. The Martins' children are all out of the "nest." The youngest, Jon, just graduated from Wisconsin at Madison and is now living and working in Texas. Joe Jr. and Judy both live and work in the San Francisco area while Jacque lives near Ann Arbor with her husband, Ed, and two children, Stephanie and Teddy.



". . . he never leaves home without a tennis racquet in hand . . ."

Diplomatic, astute, skilled lecturer, international authority, Joe gives the impression that all these remarkable traits and accomplishments have "just happened" as a matter of course, for his is an unhurried manner, an almost unbelievable controlled "ease," and a sincere concern for his fellow man. It is clear that this outstanding educator and this grand gentleman lives his life by the Golden Rule.

Indeed, the Department of Chemical Engineering at the University of Michigan is extremely proud and deeply honored to count Joseph J. Martin as one of its members. □

ChE department

UNIVERSITY OF CINCINNATI

STANLEY COSGROVE (Editor),
DAVID GREENBERG, ROBERT DELCAMP,
ROBERT LEMLICH, WILLIAM LICHT
University of Cincinnati
Cincinnati, OH 45221

CHEMICAL ENGINEERING IS one of ten engineering programs administered by six departments within UC's College of Engineering. We share a proud history as a municipal university dating back to 1819. By tradition and location it was, and still is an urban university, situated about four miles from the city center on a compact hilly campus adjoining Burnet Woods. Located in the southwest corner of Ohio, UC has strong ties with contiguous areas of both Indiana and Kentucky. During the post World War II expansion era, it grew in size and diversity, and as a State affiliated university derived a progressively increasing amount of its revenues from state funds. In 1977 this transition to a State University was completed and UC, along with Ohio State University is now one of Ohio's two "Comprehensive Universities." Total student enrollments (including about 16,000 part-time students) are close to 40,000, of which about 3000 are in engineering. Undergraduate students in chemical engineering number about 400; graduate students about 60.

While the first instruction in engineering (civil) was offered as early as 1875, 1906 is the date of major historical significance. In September of that year, young Dean Herman Schneider initiated the first co-op engineering program with 12 ME, 12 EE and 3 ChE students. This co-op work experience soon became mandatory—it still is 75 years later.

In its formative years, and until the 1960's, the College of Engineering functioned as a self-sufficient unit of the University. Its instructional periods (terms) were much shorter than the traditional semesters of the College of Arts and Sciences, and engineering students had no instructional contact with fellow students in other Colleges. This period of relative isolation ended in 1963 when most units of the University changed to a common quarter system.

DEPARTMENT HISTORY

CHEMICAL ENGINEERING AT Cincinnati has a long and notable history. The department is an outgrowth of courses given in the Chemistry Department prior to 1921. In that year Dean Schneider appointed Reuben S. Tour as the first Head of a Department of Chemical Engineering. Tour, who had extensive experience in process development during and after World War I, had been a student of A. H. White at Michigan. He may therefore be regarded as belonging to the second generation of "fathers" of Chemical Engineering Education in the U.S.

The five-year co-op program which he started led to the baccalaureate degree of Chemical Engineer in recognition of the industrial experience involved. The curriculum was on the first list of those accredited by the AIChE in 1925, and this accreditation has been maintained since that date. Graduate study for the PhD was offered as early as 1933.

In order for all of the co-op programs to provide for the required periods of industrial employment alternating with those of academic study, it was necessary to operate the college on a different calendar than the rest of the university. Tour thus had to provide not only a faculty of chemical engineering, but also a faculty in the department to teach *all* chemistry courses for *all* engineering students. In the late twenties two metallurgy professors were added. The college also had its own Department of Mathematics and Mechanics. From the beginning, therefore, the program was a well-integrated blend of basic science and engineering with a strong mathematical background.

Thus conceived on what proved to be sound and enduring principles, the department flourished. It survived the Great Depression and World War II intact, although both student body and faculty were reduced during those periods. After the war, Metallurgical Engineering began to grow independently, first as an option and later as a degree program of its own. In 1947 the name of the department was changed to Chemical and Metallurgical Engineering.

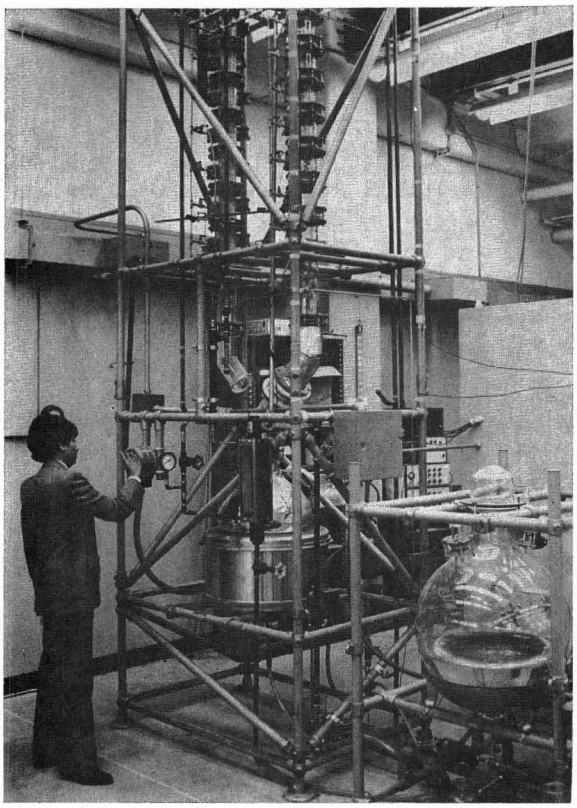
Tour died rather suddenly in 1952 and was succeeded as Head by William Licht, a Cincinnati graduate. He served until 1967, during which period important evolutionary changes occurred. The co-op calendar was gradually modified until finally the entire university adopted a uniform quarter calendar. This opened up greater opportunities for engineering students through course work in other colleges, in particular chemistry and humanistic social courses. Graduate programs in Materials Science and in Nuclear Engineering developed and grew until in the mid-60's the department was administering degrees in four fields. In 1967 a separate Department of Metallurgical Engineering and Materials Science was created and the original department was renamed Chemical and Nuclear Engineering. Thus another era came to an end.

James H. Leonard, a chemical engineering alumnus with a doctorate in nuclear engineering, succeeded William Licht as Head of the department. He served until 1973, during which time

Engineering (Rhodes Hall)

two significant events occurred. In 1970, the department moved from the facilities it had occupied in the Chemistry Building for nearly 50 years to a consolidated engineering complex in new Rhodes Hall—a building designated as "The Industrial Research Laboratory of the Year" by *Industrial Research* magazine. These well-designed and equipped quarters provided needed physical facilities to support the academic and research activities of the department. In 1971, a baccalaureate degree program in nuclear engineering was established to complement the ongoing graduate level program.

David B. Greenberg, most recently a faculty member at LSU, became the fourth Head of the department at the inception of the nationwide enrollment explosion in engineering colleges. During his headship term, the undergraduate enroll-



High Bay; Distillation Column

ment nearly doubled to more than 400, and the graduate population increased by fifty percent to over 60 students.* The annual award of 75-80 ChE and 15-20 BS NE degrees during the past several years represents a high water mark in the history of the department.

DEPARTMENTAL FACILITIES

THE DEPARTMENT, HOUSED primarily in an award winning facility, is unusually well endowed with a broad spectrum of laboratories, equipment, and instruments for both teaching and research.

Among these special academic facilities are a high bay area lab which houses a 14-plate computer-controlled glass distillation column, and a variety of other experimental apparatus for unit operations and transport studies. Significant among these are unique two-phase flow and mercury-loop heat transfer systems; both are under the research direction of Dr. Weisman. In addition to this large facility there are over 20 other smaller graduate research and teaching laboratories. Included in this group are laboratories for the study of high-temperature, high-pressure kinetics and catalysis, foam and bubble fractionation (Dr. Lemlich), biomedical, bioengineering, polymer chemistry and physics (Dr. Fried), and an unusual laser irradiation facility for chemical, biochemical, biological, and biomedical research under the direction of Dr. Greenberg. The department also has an analytical services laboratory, as well as electronics and machine shop support.

Various other industrial and government laboratories in the community are available, such as those at the Robert A. Taft Sanitary Engineering Center, the National Environmental Research Center of the Environmental Protection Agency, the Ohio River Division of the Corps of Engineers, and the Ohio River Valley Water Sanitation Commission.

Finally, in connection with the department's unique graduate co-op program, tailored to the particular needs of individual projects, participating companies often provide key educational and research facilities for joint industry, student, and faculty use.

THE UNDERGRADUATE PROGRAM

IN THE TRADITION OF all engineering programs at the University of Cincinnati, chemical engineering has been a five-year cooperative educational program since its inception. Co-op experience is considered a vital educational component of the program and is required of all students. Under the current quarter system, there are 12 quarters of on-campus study and up to seven quarters of related co-op experience (i.e., Professional Practice). Following the three study quarters of the freshman year, a student may elect to commence professional practice and acquire a maximum of seven quarters of co-op experience, or delay entrance until midway of the sophomore year and participate in the standard six quarters. Professional Practice is completed by the end of the fourth year, and all students are in school for the three quarters of the senior year.

During the latter half of the 1970's, undergraduate enrollment doubled to about 400, resulting in excessively large classes in the upper years. Current freshman admission has been deliberately reduced, resulting in the present class of 85 of the best qualified applicants. Nearly 40% come

*Dave Greenberg has relinquished the headship position as of October 1981, in order to devote his full efforts to teaching and research. The department is currently searching for a new Head.

from the greater Cincinnati area and 60% of the rest from other sections of Ohio, with approximately one-third being women and/or minorities. UC's widely known co-op program attracts students from the majority of midwestern and eastern states, and from beyond.

The curriculum is continually reviewed and undergoes periodic revision. The most recent revision was put into effect in the fall of 1979 and stipulates a minimum of 201 quarter credit hours. The Cincinnati curriculum has traditionally placed emphasis on a strong background in mathematics, basic sciences and engineering sciences, followed by rigorous chemical engineering theory and practice. The faculty relies heavily on the co-op experience that each student receives to supplement courses in engineering practice. The freshmen year consists of calculus, chemistry, physics and English. Additional chemistry and the engineering sciences, humanities and social sciences are scheduled throughout the remaining nine quarters. The student takes the first chemical

Departmental Laboratory

engineering course (material and energy balances) in the second half of the sophomore year. The remaining chemical engineering course work in thermodynamics, transport phenomena, equilibrium processes, reaction engineering, process dynamics and ChE systems follows in a logical sequence, integrated with meaningful laboratory work. The curriculum culminates with the design project in the senior year. Technical options account for 40% of the senior year curriculum and allow the student the opportunity to pursue course work related to career interests, including preparation for graduate study, which is strongly endorsed and encouraged by the faculty.

The co-op assignments provide immeasurable assistance in helping students develop a mature

In 1970, the department moved . . . to a consolidated engineering complex in new Rhodes Hall—a building designated as "The Industrial Research Laboratory of the Year" . . .

attitude and meaningful career objectives. In addition, an insight into the profession of chemical engineering is gained through an active student chapter of AIChE with strong support from the local (Ohio Valley) section of AIChE. Women students also participate in a student chapter of SWE. The total five-year program at Cincinnati provides a unique opportunity for a student to acquire not only a sound education but also knowledge of the career path that will best suit his or her interests. This knowledge has led approximately 30% of recent graduates to accept employment with their last co-op employer. It is gratifying that many have risen rapidly to responsible technical or management positions. A program of Distinguished Alumni Awards, initiated in 1969, recognizes annually those graduated who have had outstanding professional careers.

THE GRADUATE PROGRAM

THE GRADUATE STUDENT body in chemical engineering currently numbers about 45 full-time MS/PhD candidates and 20 or 30 part-time evening students taking individual courses. An MS degree may also be obtained through evening work only, with a non-thesis option available only to students who are employed professionals.

Approximately half of the current full-time students are foreign nationals from India, Taiwan, Pakistan, Viet Nam, Iran, Indonesia and Latin America—truly a cosmopolitan group. Among the U.S. students, four are classed as being in minority groups. There are six full-time and several part-time women students.

There is also a selected group of non-traditional students who do not have BS degrees in ChE. Most of them are chemists; a few are from other fields of science or mathematics. Each of them completes an individually tailored program of undergraduate engineering courses for

In the tradition of all engineering programs at the University of Cincinnati, chemical engineering has been a five-year cooperative educational program since its inception. Co-op experience is considered a vital educational component of the program . . . required of all students.

about one full year (including a recently instituted "Elements of Chemical Engineering for non ChE majors" course), before being granted full acceptance into the graduate degree program. Experience indicates that most of those will make a satisfactory transition into engineering.

In recent years 3-4 PhD's and 15-20 MS degree have been awarded each year. The current trends seem to be upward, especially because of success with the non-traditional students mentioned above.

Financial support to students is available in the form of University scholarships and assistantships, industrial grants, and endowed funds. Several very attractive Fellowships are available because of generous unrestricted support from Procter & Gamble, Exxon, DuPont, Monsanto and other companies. In addition there is a type of graduate co-op program involving industrially sponsored specific research projects. These have included arrangements with Richardson-Merrell, Atlas, PPI, and Procter & Gamble among others.

FACULTY AND RESEARCH

Stanley Cosgrove (D. Phil. Oxford University); research interests in the area of engineering applications of polymers: stabilization and destabilization, radiation effects and hazardous waste stabilization.

Robert Delcamp (M.A., Ph.D., University of Cincinnati); administrative posts have included Assistant, Associate and Acting Dean of the College; research interests in industrial organic chemistry with special emphasis on microbiological processes.

Joel R. Fried (B.S., M.E., RPI; M.S., Ph.D., University of Massachusetts); research interests in the study of polymer blends.

Rakesh Govind (B.Tech., Indian Institute of Technology (Kanpur); M.S. (ChE), Ph.D., Carnegie Mellon University); research interests in the area of process synthesis and control.

David Greenberg (Carnegie Tech, The Johns Hopkins University, and Louisiana State University); current research interests include laser chemical, biochemical, biological and biomedical studies; active research in the conservation and environmental fields with interests in solar energy, storage projects and membrane transfer studies.

Daniel Hershey (B.S., Cooper Union; Ph.D., University of Tennessee); current interests are in gerontology, concentrating on research in basal metabolism, entropy, and life expectancy as related to dieters, smokers and joggers, and to aging systems such as corporations and civilizations.

Yuen-Koh Kao (BSChE, National Taiwan University; M.S., Ph.D., Northwestern University); research interests are in the general area of mathematical analysis of chemical engineering problems and current research areas are digital process control, transition boiling heat transfer, transport phenomena of electrochemical systems, and heat transfer problems of catalytic reactors.

Soon-Jai Khang (B.E., Yon Sei University in Korea; M.S., Ph.D., Oregon State University); research interests are primarily in the area of chemical reaction engineering, including heterogeneous catalysis and mixing and flow patterns.

Robert Lemlich (BChE, New York University; MChE, Polytechnic Institute of Brooklyn; Ph.D., University of Cincinnati); research interests are primarily in the area of foam separation and properties.

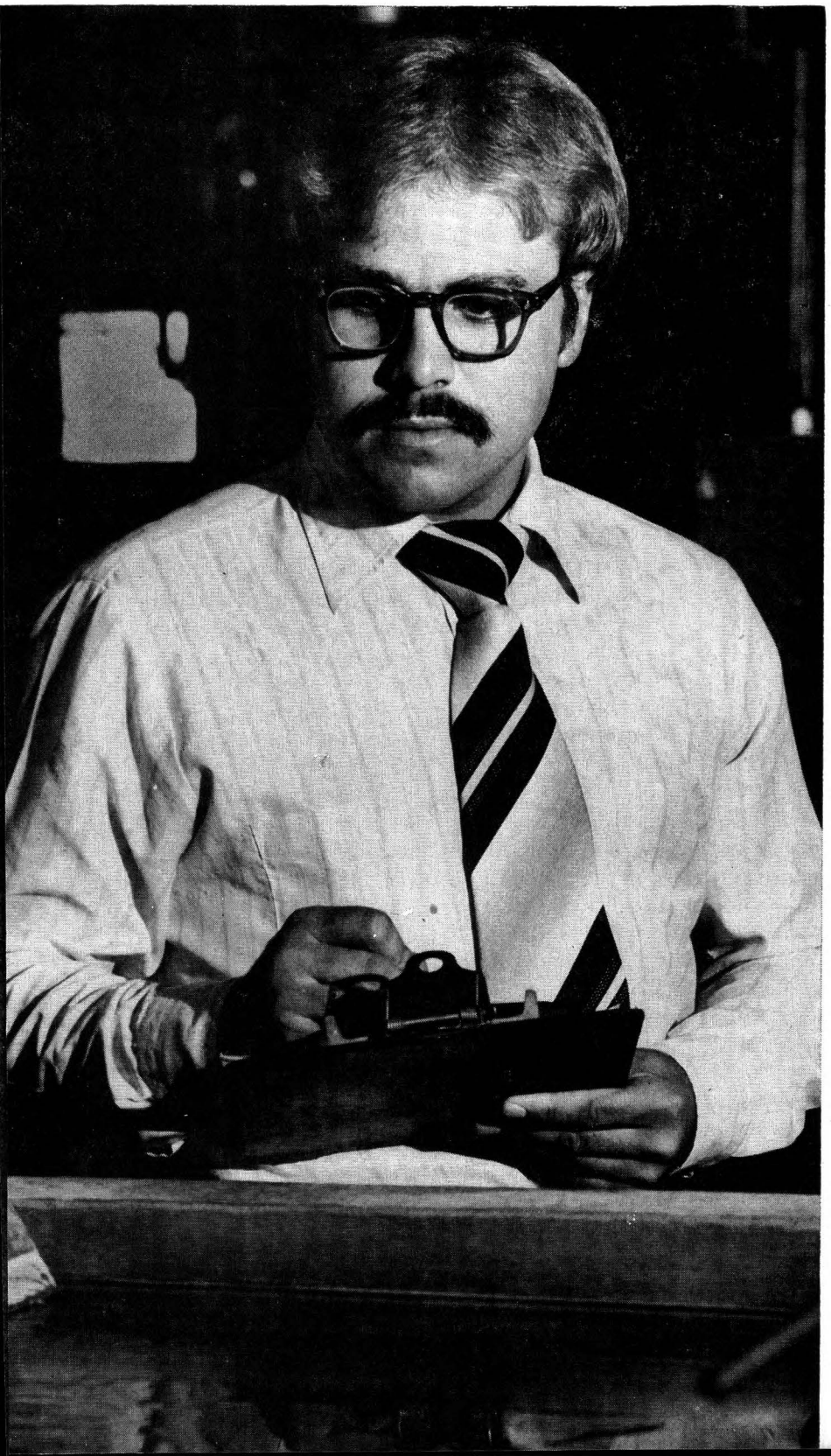
William Licht (Ch.E., M.S., Ph.D., University of Cincinnati); Department Head; 1952-1967. Since 1967 he has devoted efforts to the field of air pollution control, which culminated in 1980 with the publication of a book "Air Pollution Control Engineering—Basic Calculations in Particular Collections."

Joel Weisman (BChE, City College of New York; MS, Columbia University; PhD, University of Pittsburgh); research has been in the areas of nuclear reactor thermal design and safety, boiling heat transfer, and two-phase flow.

Despite some pessimistic predictions for engineering education in the '80's, we enter this decade with strong feelings of optimism. We look back with pride, and to the future with the conviction that chemical engineering at Cincinnati will prosper in a University and industrial community which are both highly supportive of our efforts. □

"Can a new plastic be produced efficiently? It's up to me to decide."

Mark Carlson BS, Chemical Engineering



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Award Lecture

DESIGN RESEARCH

Both Theory and Strategy

The 1981 ASEE Chemical Engineering Division Lecturer is Arthur W. Westerberg of Carnegie-Mellon University. The 3M Company provides the financial support for this annual lecture award.

A native of Minnesota, Art received his B.Sc. from the University of Minnesota in 1960, his M.Sc. from Princeton in 1961 (both in chemical engineering), and his Ph.D. in 1964 from Imperial College, London.

Returning to Minnesota, he was president of a consulting company for nine months before joining Control Data Corporation as a senior analyst in their process control division. In 1967 an interest in teaching and research drew him to academia and he joined the chemical engineering department at the University of Florida.

In 1974-75, he spent a sabbatical at the Computer Aided Design Centre in Cambridge, England, at which time he coauthored Process Flowsheeting, *a unique book devoted to elucidating the underlying structures and their advantages for available and proposed flowsheeting programs.*

In 1976 Art joined Carnegie-Mellon University where he served as director of the Design Research Center until becoming head of the chemical engineering department in 1980.

In research, his publications emphasize optimization and synthesis in computer-aided design. Recent work includes developing a multileveled decomposition strategy to permit an optimization algorithm to be useful for engineering design calculations, the development of a new flowsheeting system, and a new approach for estimating minimum utility requirements.

He was on the CACHE Committee from its inception in 1970 until last year, and was program chairman for the ChE Division of ASEE Annual Conference in 1979. He gave the first invited "Tutorial Lecture" in 1978 at the Vancouver ASEE meeting and has authored several articles for CEE.

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THIS PRESENTATION is an opportunity to be philosophical about design, an opportunity not to be missed. The ideas to be given here are my version of ideas generated both in my own work and during several lively discussions with James Douglas (University of Massachusetts) and Bodo Linnhoff (Imperial Chemical Industries).

Design research is often narrowly viewed to be research to develop theory supporting computational methods useful for performing design calculations. The methods might be new convergence techniques, better stiff ODE integration methods, new optimization algorithms particularly well suited for systems of interconnected units, and so forth. Even the relatively new area of process synthesis is frequently viewed as solvable by using similar ideas, but perhaps using techniques which allow for a number of the variables to take on only discrete values.

The significant questions relating to synthesis were aptly stated by Simon (1969) and are further amplified in Motard and Westerberg (1978). They are 1) how does one represent the alterna-

tive configurations permitted when developing a design, 2) how does one establish a value for each alternative so as to identify which are the better ones, and 3) how does one search among the enormous number of alternatives one is certain to create.

The guidelines we wish to state here speak principally to the third issue and partly to the second. We hope to show that powerful guidelines do exist which can be used to solve most open ended design problems directly or which can be used to design and evaluate aids and strategies which will be useful for solving such problems.

We conjecture that these guidelines can be taught; we (I. Grossmann and the author) attempt to do just that in our undergraduate and graduate design classes. We hope also to convince the reader that this aspect of design research is a valid contribution but one frequently avoided or understated when presenting new results.

THE GUIDELINES

WE OFFER THE FOLLOWING five guidelines to use when solving design problems.

1) **Evolve from simple to complex**
2) **Use a depth-first approach**
3) **Develop approximate criteria either as targets or heuristics for screening among alternatives**
4) **Use "top down" design techniques alternatively with "bottom up" ones.**
5) **All things being equal, make optimistic assumptions.**

We shall now explain each of these ideas in more detail and then, for the rest of the paper, examine their application to several examples. If the guidelines are true, then one should be able to use them to design a means to demonstrate their own validity; i.e., the ideas should be recursive.

Evolve from Simple to Complex

All earlier calculations for a design should be done using simple calculations even if one knows them to be quantitatively incorrect. The earlier calculations are for learning about the design qualitatively. Many of the major decisions can be made obvious by use of approximate calculations only. Hardly anyone experienced in design violates this guideline for long in practice, but when they do, failure to complete the needed calculations frequently results.

An obvious example is to prepare an outline to a research paper before writing it.

Douglas . . . conjectures that 99% of all initial design concepts will prove to be technologically or economically unsatisfactory . . . The correct mindset . . . is to try to prove concepts will not **work.**

Use a Depth-First Approach

This guideline suggests one should go directly for a first feasible solution to the problem at hand, based on a sequence of best local decisions. One should *avoid the tendency to backtrack* at any point prior to finding an initial complete solution to the problem. (Outline the whole report.)

The reasoning is as follows. The initial design is an enormously effective learning device; it gives the designer his first glimpse as to the steps which are easy and to those which are the important difficulties to be encountered in the problem, with perhaps some difficulties being insurmountable. In this latter case, the design can be abandoned with minimal work expended.

"Depth first" is a term used to search a tree of decisions. It is a search strategy in opposition to "breadth first" searching. Breadth first allows backtracking prior to completing the first design if earlier decisions no longer appear to be likely winners.

To repeat this guideline—generally avoid backtracking. Go as quickly as possible to the first potential solution.

These first two guidelines permeate the recent publications by Douglas as well as the lecture notes for our own undergraduate design course.

Develop Approximate Criteria

One reason the design question is difficult to deal with is that design is caught in a dilemma. The final criteria used to assess the value of a design (if the criteria can be stated) cannot be evaluated without having in hand a completed design. Thus one must make initial decisions which one can only hope will result in solutions that are a good compromise with respect to the final criteria. To carry out the initial design, alternative approximate criteria must of necessity be used. Often these are in the form of heuristics. At other times they can be locally realizable targets.

A significant research contribution can be the discovery of effective approximate criteria, as we shall see has occurred in the synthesis of heat ex-

changer networks. The *targets themselves* may be considered the initial simple calculations needed for the earlier design stages. Linnhoff, in his research publications, is a vociferous advocate of target setting.

Use Top Down/Bottom Up Design Alternatively

Top down and bottom up design are forms used to describe how to design computer programs. The former, top down, refers to starting at the highest level with the overall goal of the design. This goal is then partitioned into subgoals, which, if solved, will accomplish the higher goal. These subgoals are then each treated as the top level goals to be further partitioned, etc., until lowest level subgoals are discovered which can be implemented without further partitioning.

Bottom up design is to design first the lowest level building blocks which one assumes will be necessary to accomplish the design. In computer programming, writing a linear equation solving subroutine first would be part of a bottom up strategy for designing a nonlinear equation solving package, where one assumes such a subroutine will be needed.

Design research is often narrowly viewed to be research to develop theory supporting computational methods useful for performing design calculations.

What is being advocated here is to use the two strategies alternatively. The top down strategy should be used to scope out the alternatives in terms of high level tasks needed to solve the design. Once set, then bottom up design should be used to *locate bottom level subtasks which will preclude a solution.* Thus they will, for minimal effort, rule out an alternative suggested by top down design. To solve a bottom level subtask requires guessing the environment for the bottom level subtask.

Be Optimistic

Douglas (1979) conjectures that 99% of all initial design concepts will prove to be technologically or economically unsatisfactory—i.e., they will fail as concepts. The correct mindset, and one a designer usually fails to have, is to try to prove concepts will *not* work.

When attempting to use bottom up design to rule out design concepts, one should use optimistic guesses as to the environment for the bottom level task. If the task cannot succeed when being optimistic, then the failure to do the task can be used to rule out the top down concept requiring it. If one uses conservative guesses, and the bottom level task proves difficult, it may be because of the use of an overly conservative set of guesses as to the task environment, and thus one would be unable to use its behavior to rule out the concept.

A corollary to the above guidelines is that one should use the information learned from the original solution to move to subsequent improved solutions, using in one form or another a learning or evolutionary approach.

A second corollary to the above guidelines is that computer aided process design programs which do not cater to them will be significantly less useful than those which do.

The design problem is one of searching an enormous space of alternatives to select the correct building blocks and their interconnection, as well as also searching the space of continuous variables to establish the levels at which to operate any given structure. The guidelines are consistent with the following specific search strategy.

1) **Select a limited technology within which to solve the problem.**
2) **Using heuristics sketch a good initial solution from within the allowed technology.**
3) **Examine this solution and develop alternative solutions by revising within the allowed technology or within a modified allowed set of technology, where the initial solution suggests the allowed set modifications. Iterate from Step 2 until a "best" solution is found.**
4) **Repeat Steps 2 and 3 using more complete models.**

The guidelines also support the following specific strategy.

1) **Select a limited technology within which to solve the problem.**
2) **Within this technology set up a superstructure within which is embedded all the alternatives of interest. Use heuristics to eliminate obviously useless portions of the superstructure as it is being developed.**
3) **Use algorithmic methods to discover the best substructure from among the alternatives embedded in the superstructure.**
4) **Examine the solution and develop modifications to the allowed technology within which to search.**
5) **Return to Step 3 until no improvements are possible.**
6) **Iterate Steps 2 to 5 with more complete models.**

(Steps 3 and 4 can be very mathematical, giving rise to the development and use of sophisticated theorems, and thus perhaps satisfying many

persons that quality abounds in the results.)

The advantage to this last approach is that parallel decisions are made in Step 3 so in a sense an optimal solution is found, but it is found by looking among a rather small set of alternatives. Fallible heuristics are used only to make the more riskfree problem reductions.

The sequential aspects to the approach are to learn which technological alternatives ought to be in the superstructure and to solve initially using simple models to get closer to the final solution before starting to do complex calculations.

EXAMPLES

WE SHALL NOW DESCRIBE four example "design" problems to illustrate the effectiveness of the guidelines.

An Entire Chemical Process

The first example is to scope out a process to hydrolyze ethylene (EL) to ethyl alcohol (EA) via the reaction at 560 k and 70 atm

$$CH_2 = CH_2 + H_2O \rightarrow CH_3CH_2OH$$

or

$$EL + W \rightarrow EA$$

The available ethylene feed contains one mole percent methane (M) and three mole percent propylene (PL). Propylene also hydrolyzes to iso-propyl alcohol (IPA) but to a lesser extent at the given reactor conditions. Croton aldehyde (CA), a C_4 aldehyde, forms as a trace byproduct. Diethyl ether (DEE) forms in equilibrium with water and ethyl alcohol:

$$2CH_3CH_2OH \rightleftharpoons CH_3CH_2OCH_2CH_3 + H_2O$$

or

$$EA \rightleftharpoons DEE + W$$

Conversion of the ethylene is from 5 to 7%, with water in significant excess in the reactor feed.

Skipping lightly over many details, we start our design by scoping out the process using a top down view, getting at least the three structures illustrated in Fig. 1.

Remembering that the strategy being advocated suggests striking out for a completed design without backtracking, we must select one of these sketches (or a variant); we use a bottom up design technique to rule out alternatives. We look for reasons a concept will likely fail and do a quick bottom level calculation to validate our conjecture, guessing the most optimistic environment

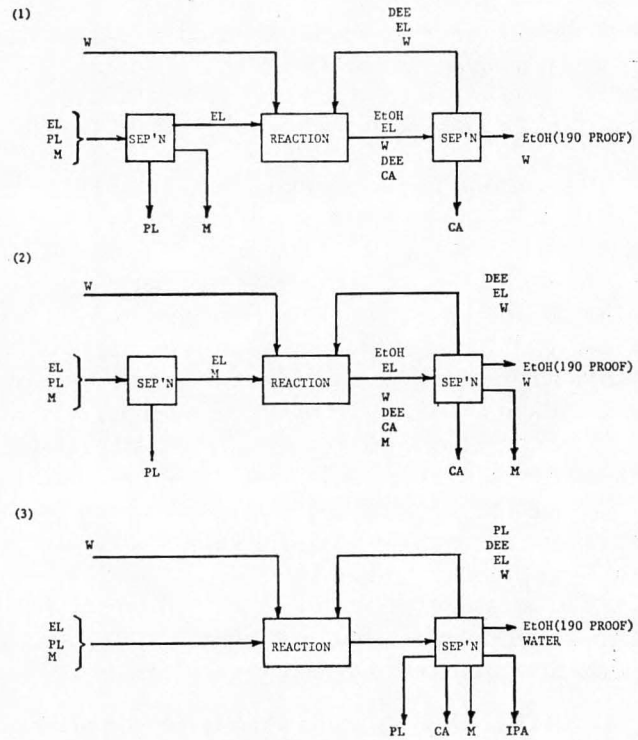

FIGURE 1. Top Down Sketches for Ethylene to Ethyl Alcohol Process.

we can for that calculation.

The first two variants in Fig. 1 look as if they might fail because of the extremely low temperatures which may be required if we were to use distillation to effect the initial separation step. We need only a Mollier diagram for ethylene to see that at $P < P_c = 50.7$ atm, the highest temperature possible at the top of an ethylene/propylene column is 0°C. Refrigeration would be required, and, as an approximate criterion, we rule out using refrigeration if possible. The third option, if volatilities are examined, could be implemented to remove the methane and propylene by recycling them back with the ethylene to the reactor. Since methane is an inert here, it would build up and could be removed by bleeding it. The propylene will both convert to iso-propyl alcohol and be lost in part in the bleed. Finally comparing boiling points for water, iso-propyl alcohol, and the azeotope of water and ethyl alcohol suggests this separation is possible. All other separations look rather straightforward. We adopt option 3.

An automatic synthesis program for developing total flowsheets should be able to come quickly to this same result. If not, it must be working too hard. Remember this flowsheet is not purported to be the best one, only a good first one from

which we intend to learn about the process so our second guess as to the solution is done with much improved insight.

Separation System Synthesis

The second process example we shall look at is separation system synthesis. We have an obvious candidate in our previous example, the separation of methane, propylene, ethylene, diethyl ether, ethyl alcohol, water, iso-propyl alcohol and croton aldehyde into the product ethyl alcohol, a recycle of ethylene, diethyl ether and water, and the by-products of methane, propylene, iso-propyl alcohol and croton aldehyde. The separation step of the third option in Figure 1 illustrates the problem. Note the feed to that step is vapor at high pressure and the recycle is also a vapor which needs to be returned at high pressure.

The strategy we now look at will be the first one stated earlier, one we claim is consistent with the guidelines given:

1) **Select a technology within which to solve the problem.**
2) **Using heuristics, sketch a good candidate solution. Evaluate it.**
3) **Examine the solution and develop alternate solutions by revising within the allowed technology or by adding new technology.**

If we were trying to develop our earlier flowsheet fully, we would likely skip Step 3 above because it represents backtracking. If, on the other hand, the separation problem is our entire design problem, Step 3 is a refinement step, one that follows our having a first complete solution.

Fig. 2 sketches a possible solution to the above separation problem using distillation technology.

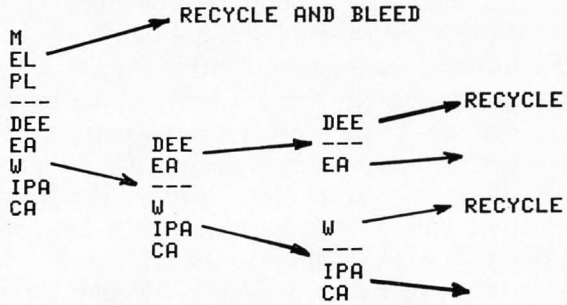

FIGURE 2. First Sketch for Separation System.

The heuristics used are ranked in order of importance and are a paraphrase and subset of those in Seader and Westerberg (1977). For the next separation

1) **do the easy split or**
2) **remove the most bountiful component or**
3) **remove the most volatile component.**

The split between diethyl ether and ethyl alcohol can be done easily; do it first. The recycle can tolerate methane and propylene so let them recycle, but then remove methane using a bleed stream. Go after the water which is plentiful

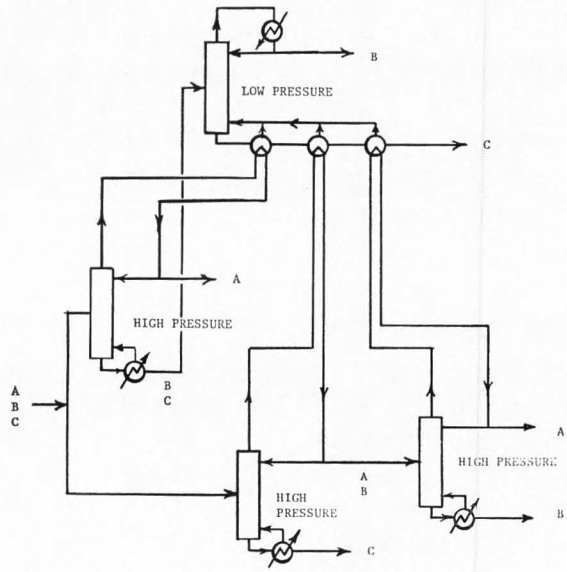

FIGURE 3. Highly Heat Integrated Distillation Scheme Using Multiple Effect Columns.

next but, using heuristic 3 also, split above it to remove the ethyl alcohol. Finally split off the water from IPA and CA.

At this point let us consider the separation problem as the whole problem we are solving. For this problem Mark Andrecovich, a Ph.D. student of mine, is discovering that the second strategy stated earlier, where one creates a sequence of superstructures to be optimized, seems to be very effective. Figure 3 illustrates the solution found to a 3 component separation using this approach. It is 11% less expensive than all obvious competitors on an annualized cost basis which considers both investment and operating costs. Note the complexity of this structure. The research question is to establish a means to locate it quickly. □

EDITOR'S NOTE: The final two examples in this Award Lecture, and Professor Westerberg's concluding remarks will appear in the Spring '82 issue of Chemical Engineering Education.

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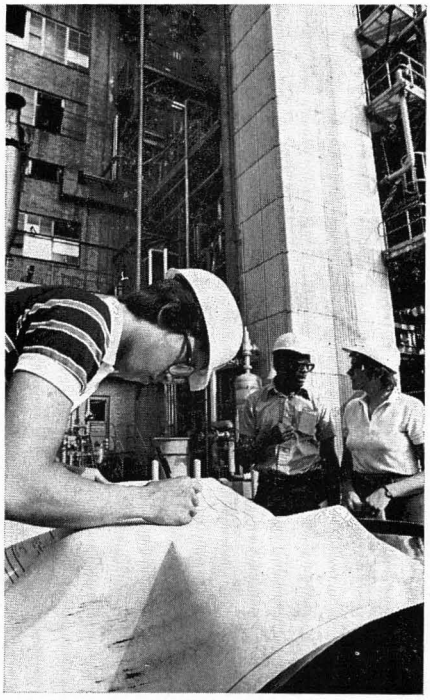

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THERMODYNAMICS OF RUNNING

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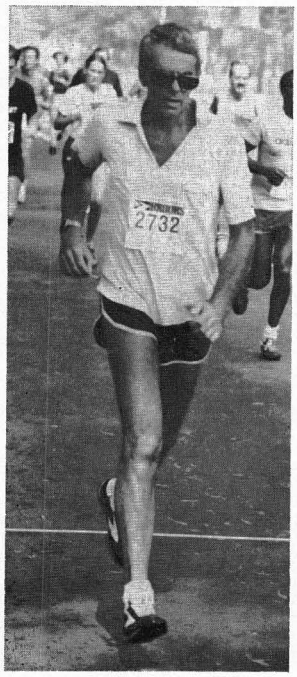
TEXTBOOKS ON THERMODYNAMICS for chemical engineers contain numerous examples of the application of the first and second laws. These include chemical reaction, refrigeration, liquefaction, compression of gases, various power cycles (Brayton, Otto, Rankine), pipe flow and throttling. Recently chemical engineers have become interested in bioengineering. Therefore it is useful to add to this list an application to a biological system. Several problems suitable for classroom discussion are provided.

DIMENSIONAL ANALYSIS OF RUNNING

PHYSIOLOGICAL WORK PERFORMED during aerobic running is an excellent example of a biological process which can be analyzed thermodynamically in the same manner as other power cycles. In running, each step or stride constitutes a cycle.



Alan L. Myers did his undergraduate work at the University of Cincinnati after three years in the U.S. Navy during the Korean War. He obtained his Ph.D. at the University of California at Berkeley in 1964 and then joined the faculty at the University of Pennsylvania. His research specialties lie in thermodynamics and statistical mechanics, particularly adsorption and electrolyte solutions. Other interests include Russian language and literature, and also long-distance running. Alan runs several miles each day and has competed in many races, including the 1981 New York City Marathon.

The average velocity v of running, which is assumed to continue for several minutes or more until a steady state is achieved, is given by:

$$v = L\nu \tag{1}$$

where L is the length of a single stride and ν is the frequency with which the feet strike the ground. This frequency is analogous to the rpm of the drive shaft of a mechanical engine. The mechanical power of running is:

$$P_{mech} = W_{int}\nu \tag{2}$$

W_{int} is the internal work done by the muscles of the body during a single stride or cycle.

Both L and ν are functions of the velocity and other variables such as the mass (M) and height (H) of the runner. A biomechanical model of running sufficiently realistic for the numerical calculation of work would be very complicated, but some of the important dimensionless groups are identified as:

$$L^* = \frac{L}{H} = \frac{\text{length of stride}}{\text{height}} = \text{dimensionless stride}$$

$$v^* = \frac{v}{\sqrt{gH}} = \frac{\text{inertial force}}{\text{gravitational force}} = \text{dimensionless velocity}$$

$$W^* = \frac{W_{int}}{MgL} = \frac{\text{work}/(\text{unit distance})(\text{unit mass})}{\text{acceleration of gravity}} = \text{dimensionless work}$$

The relation between stride (L^*) and velocity (v^*) was established by experiments on a track. Most of the subjects were sophomore students in chemical engineering at the University of Pennsylvania, but the points plotted on Fig. 1 include measurements for children and middle-aged adults, males and females, champion athletes and non-athletes with builds ranging from slim to overweight. For each point, subjects ran one lap (400 m) at a steady pace measured by a stopwatch and L was determined by counting steps.

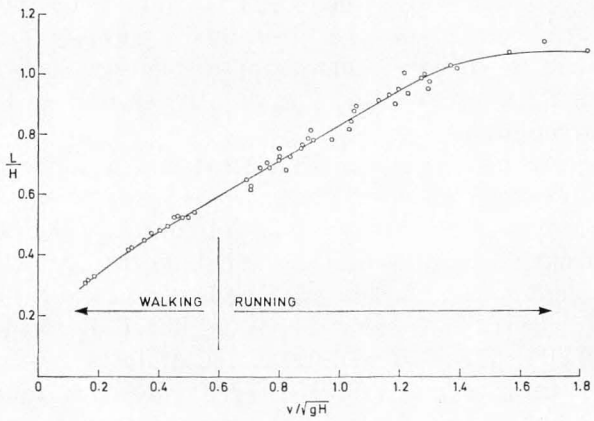


FIGURE 1. Length of stride (dimensionless) as a function of velocity (dimensionless).

The solid line drawn on Fig. 1 is the function $L^*(v^*)$. The average deviation between the points and the curve is 2%. This scatter is due to a combination of experimental error and the neglect of other variables which might affect the stride such as body proportion, obesity and training.

Fig. 1 indicates that the length of the stride L increases with velocity until it is equal to the height H of the runner. After that, it is necessary to increase the frequency ν to run faster as shown by Eqn. (1). More experimental points are needed to establish this apparent leveling-off in the length of the stride. However, the portion of the curve above $v^* = 1.4$ corresponds to sprint races less than one mile in distance and does not apply to the aerobic running under discussion. Fig. 1 also shows that the functions $L^*(v^*)$ for walking and running form a single, continuous curve, although this was not expected because the mechanics of walking and running are different.

For $v^* < 1.4$, the solid line of Fig. 1 is nearly linear:

$$L^* = (0.238) + (0.594)v^*$$

Example 1. Calculate the stride length and frequency for a person running at a speed of 15 km/hr. The mass of the person is 75 kg and the height is 1.8 m.

Using MKS units, the velocity is 4.17 m/s.

$$v^* = v/\sqrt{gH} = (4.17)/\sqrt{(9.8)(1.8)} = 0.99$$

$$L^* = 0.83 \text{ (from Fig. 1)}$$

$$L = (L^*)H = (0.83)(1.8) = 1.49 \text{ m}$$

$$\nu = v/L = (4.17)/(1.49) = 2.80 \text{ s}^{-1}$$

. . . the internal work done by the muscles is identified as the sum of three terms: work of overcoming gravity . . . work against inertial forces while accelerating, and work to overcome wind resistance . . .

WORK DONE BY MUSCLES DURING RUNNING

WORK PERFORMED BY THE muscles cannot be measured directly because it is done internally. An analogy with an automobile operated on level terrain is useful. For a car the mechanical work supplied by the engine is equal to the product of the torque transmitted to the drive shaft and its angular displacement. If the entire automobile is taken as the thermodynamic system, the work performed by the engine and transmitted to the wheels through the drive shaft is performed internally. This work is the sum of three terms: work against the drag force exerted by the wind, work to accelerate the car, and work performed to overcome rolling friction of the tires. The sum of these three terms is equal to the work done internally by the engine. Returning to the human body, work is performed internally by the muscles. Since the body is the thermodynamic system, the internal work done by the muscles (W_{int}) is identified as the sum of three terms: work of overcoming gravity (the body bobs up and down while running on level terrain), work against inertial forces while accelerating, and work to overcome wind resistance:

$$W_{int} = \Delta E_k + \Delta E_p + W_{wind} \qquad (3)$$

Increases in kinetic (ΔE_k) and potential (ΔE_p) energy are periodic, occurring once each stride, whereas work against wind resistance (W_{wind}) is steady. For running on level terrain at steady state, the time-averaged change in kinetic and potential energy is zero. The periodic increases in kinetic and potential energy are supplied by muscle work. Each time the foot strikes the running surface, there is a force against the ground but no displacement if the surface is firm. However, the body decelerates while the foot is touching the ground, and muscle work must be performed to restore the lost kinetic energy. Also, the center of gravity of the body falls a few centimeters with each stride, and again muscle work is required to regain the lost potential energy.

The kinetic and potential energy terms in

Eqn. (3) are the periodic increases which occur with each stride. What happens to the corresponding decreases in kinetic and potential energy? Once more an analogy with a car is helpful. If the car accelerates from 50 to 55 mph, the additional work required by the engine is equal to the increase in kinetic energy of the car. If the car then brakes from 55 to 50 mph, the kinetic energy decrease is dissipated as heat by the brakes and there is no work done by the engine against inertial forces until the next acceleration. The human body maintains a constant average velocity but there are periodic accelerations and decelerations at the frequency with which the feet strike the ground. The center of gravity rises and falls at the same frequency. The periodic decreases in kinetic and potential energy are dissipated as heat to the surroundings.

Physiological work performed during aerobic running is an excellent example of a biological process which can be analyzed thermodynamically in the same manner as other power cycles.

FIRST LAW OF THERMODYNAMICS

THE FIRST LAW OF thermodynamics for aerobic running at steady state on level ground is:

$$\Delta H = Q - W_{wind} \qquad (4)$$

The control volume for the first law is the body as a whole and the only work term is against wind resistance. W_{wind} is the work done by the body against the constant drag force imposed by the wind, which is self-generated by the motion of the body even in still air. It is assumed that the true wind velocity is zero, so that the wind velocity relative to the runner is equal to his average velocity v (see Appendix). The muscle work is performed internally and therefore does not appear in Eqn. (4). The periodic changes in kinetic and potential energy vanish for running on level terrain at steady state.

ΔH is the exothermic heat of reaction for the combustion of foodstuffs stored in the body. For example, for glucose:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O \qquad (5)$$

the heat of combustion is:

$$\Delta H_c = -\Delta H = 670 \text{ kcal/mole} = 3.7 \text{ kcal/g}$$

For running on a treadmill there is no wind resistance and the work term in Eqn. (4) is zero. In this case, the value of ΔH is equal to the heat transferred from the body to the surroundings (Q is negative). Thus all of the energy derived from food is eventually dissipated as heat to the surroundings.

The heat of combustion is calculated indirectly from the measured oxygen consumption. A respiration calorimeter is used to measure the rate of oxygen uptake by the lungs. According to the stoichiometry of Eqn. (5), the heat of combustion of glucose is 5 calories per milliliter of oxygen (STP). The heat of combustion of fatty acids is 4.5 calories per milliliter of oxygen. An intermediate value of 4.8 calories per milliliter is used by physiologists [10] to relate oxygen consumption to the heat of combustion of foodstuffs.

The energy generated by the combustion of carbohydrates and fats is dissipated as heat from the body to the surroundings by several mechanisms: conduction and convection, radiation, evaporation of water from the skin, and respiration. The relative importance of these different modes of heat transfer depends upon a number of factors such as amount of clothing, the temperature difference between the body and the surroundings, the humidity, etc. Nevertheless the total heat loss is given by the first law, Eqn. (4).

Example 2. In a five-minute treadmill test, a person with a mass of 65 kg consumes 14.5 liters of oxygen (STP) while running at maximum speed. Estimate the heat loss assuming steady state.

From Eqn. (4):

$$-Q = -\Delta H = \left(\frac{4.8 \text{ cal}}{\text{ml}}\right)(14{,}500 \text{ ml})\left(\frac{\text{kcal}}{10^3 \text{ cal}}\right) = 69.6 \text{ kcal}$$

The specific maximum rate of oxygen consumption is a measure of running ability because it is proportional to the power-to-mass ratio of the person. Values range from 30 ml/kg-min for below-average capability, to 60 for athletes and as high as 70 ml/kg-min for marathon runners [4]. For this example,

$$\text{Max. oxygen capacity} = \frac{(14{,}500 \text{ ml})}{(65 \text{ kg})\ (5 \text{ min})} = 44.6 \text{ ml/kg-min}$$

This is a typical value for an average person of age 25.

SECOND LAW OF THERMODYNAMICS

THE PROCESS OF RUNNING is essentially isothermal. The muscle cells are the engines that transform chemical energy into mechanical energy. The second law of thermodynamics states that the maximum work which can be derived from the oxidative reaction by the muscles is given by the decrease in Gibbs free energy:

$$W_{int} = -\Delta G = -(\Delta H - T\Delta S)$$

The maximum work is for a reversible process, so the actual irreversible work W_{int} performed by the muscles must be less than $(-\Delta G)$. The thermodynamic efficiency of running is:

$$\epsilon = \frac{W_{int}}{(-\Delta G)}$$

and the second law requires that $\epsilon < 1$. Although ΔS is large for Eqn. (5), the product $T\Delta S$ is much smaller than ΔH and in practice the efficiency is defined by:

$$\epsilon = \frac{W_{int}}{\Delta H_c} \qquad (6)$$

This efficiency can be determined by independent measurements of mechanical work and heat of combustion. The overall efficiency defined this way is 29% [10]. It is the product of two values of efficiency, one for the synthesis of ATP (60%) [8] and another for the performance of positive muscle work by contraction associated with hydrolysis of ATP (49%) [10]. This overall efficiency of 29% for converting chemical energy into mechanical work is comparable to the efficiency for producing electricity in commercial power plants by combustion of fossil fuels (30 to 40%).

DIMENSIONLESS WORK OF RUNNING

SINCE THE DIMENSIONLESS stride L^* is a function of dimensionless velocity v^*, there should be a relation between the dimensionless work and v^*. The positive internal work per stride is given by Eqn. (3). The instantaneous kinetic energy of the body is:

$$E_k = \frac{M}{2} v^2$$

The differential of E_k is:

$$dE_k = Mvdv$$

The process of running is essentially isothermal. The muscle cells are the engines that transform chemical energy into mechanical energy.

The increase in kinetic energy for each stride can be estimated from the increase in velocity:

$$\Delta E_k = Mv\Delta v \qquad (7)$$

This can be measured with an accelerometer, which is used to find the impulse imparted to it by the foot and thus the increase in momentum $M\Delta v$. The increase in potential energy with each stride is:

$$\Delta E_p = Mg\Delta z \qquad (8)$$

where Δz is the increase in elevation of the body's center of gravity above the running surface, which can be measured using high-speed photography. For the special case of running on a treadmill, the wind resistance is zero and substitution of Eqns. (7) and (8) into (3) yields the muscle work performed by the body per stride:

$$W_{int} = Mv\Delta v + Mg\Delta z \qquad (9)$$

In non-dimensional form, Eqn. (9) becomes:

$$W^* = \frac{W_{int}}{MgL} = \frac{\nu\Delta v}{g} + \frac{\Delta z}{L} \qquad (10)$$

Example 3. The person described in Example 1 ran on a treadmill at a steady speed of 15 km/hr. The stride length was 1.49 meters and the frequency was 2.80 strides per second. Measurements with an accelerometer and high-speed photography indicated that the increase in elevation of the center of gravity of the body was Δz = 6.6 cm, and the increase in velocity with each stride was Δv = 0.79 km/hr. What is the mechanical power expended and what is the dimensionless work of running at this velocity?

Using MKS units, the velocity is 4.17 m/s and Δv = 0.219 m/s.

$$W_{int} = Mv\Delta v + Mg\Delta z$$
$$= (75)(4.17)(0.219) + (75)(9.8)(0.066)$$
$$= 117 \text{ J/stride}$$
$$P = W_{int}\nu = (117)(2.80) = 328 \text{ watts}$$
$$= \text{mechanical power}$$

$$W^* = \frac{\nu\Delta v}{g} + \frac{\Delta z}{L} = \frac{(2.80)(0.219)}{(9.8)} + \frac{(0.066)}{(1.49)}$$
$$= 0.107$$

MECHANICAL POWER AND ENERGY EXPENDITURE

THE DIMENSIONLESS WORK OF running ($W^* = 0.107$) calculated in Example 3 is for a particular velocity. Since L^* is a function of v^*, it was anticipated that W^* would also be a function of v^*. Surprisingly, experiments have shown [2, 5] that the kinetic energy term in Eqn. (10) increases with velocity and the potential energy term decreases with velocity such that the sum of both terms is nearly constant. Thus it is a good approximation to assume that the dimensionless mechanical work of running is a constant, independent of velocity:

$$W^* = 0.107 = \text{constant} \tag{11}$$

Substituting Eqn. (11) into (2):

$$P_{mech} = W_{int}\,\nu = W^*Mgv \tag{12}$$

According to Eqn. (6), the rate of energy consumption derived from oxidation of carbohydrates and fats is:

$$\frac{dE}{dt} = \frac{W^*Mgv}{\epsilon} \tag{13}$$

where $W^* = 0.107$ and $\epsilon = 0.29$. Eqns. (9) - (13) apply to running on a treadmill for which there is no work against wind resistance. As shown in the Appendix, the mechanical power necessary to overcome self-generated wind resistance is:

$$P_{mech} = \frac{2}{\sqrt{\pi}} C_d \rho_a v^3 \sqrt{\frac{MH}{\rho_b}} \tag{14}$$

where C_d = drag coefficient of the body = 0.50, ρ_a = density of surrounding air, and ρ_b = density of body $\simeq$ 1000 kg/m^3. Therefore the total mechanical power required for running in still air is given by the sum of Eqns. (12) and (14):

$$P_{mech} = W^*Mgv + \frac{2}{\sqrt{\pi}} C_d \rho_a v^3 \sqrt{\frac{MH}{\rho_b}} \tag{15}$$

The total energy expenditure of running is obtained by dividing the mechanical work by the efficiency (29%).

Another interesting variable is the total energy expenditure per unit distance:

$$\frac{E}{L} = \frac{W_{int}}{L\epsilon} = \frac{W^*Mg}{\epsilon} + \frac{2}{\sqrt{\pi}} \frac{C_d \rho_a v^2}{\epsilon} \sqrt{\frac{MH}{\rho_b}} \tag{16}$$

Eqn. (16) shows that the energy expenditure of running (per unit distance) versus velocity is the equation of a parabola with its vertex at $v = 0$,

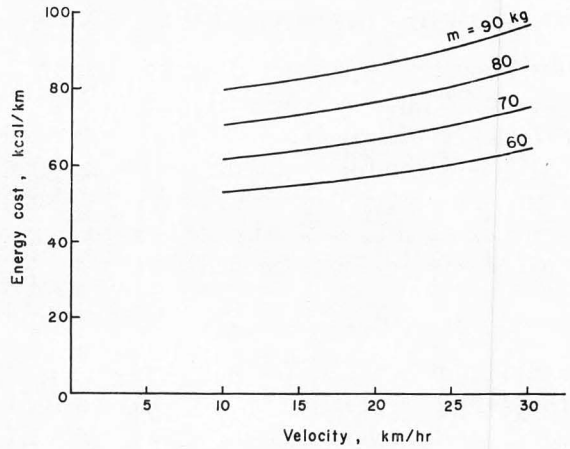


FIGURE 2. Net energy cost for running (less resting metabolism) for adult human.

as shown on Fig. 2. Eqn. (16) is in good agreement with data reported in the literature [6].

Example 4. For the person described in Example 1, calculate the mechanical power and the total energy expenditure for running at a velocity of 15 km/hr.

The mechanical power is given by Eqn. (15). For MKS units:

$$\begin{aligned} P_{mech} &= (0.107)\,(75)\,(9.8)\,(4.17) \\ &\quad + \frac{2}{\sqrt{\pi}}(0.5)\,(1.184)\,(4.17)^3 \left(\frac{(75)\,(1.8)}{1000}\right)^{1/2} \\ &= 346 \text{ w.} \end{aligned}$$

The energy expenditure per unit distance is given by Eqn. (16) or by:

$$\begin{aligned} \frac{E}{L} &= \frac{W_{int}}{L\epsilon} = \frac{P_{mech}}{v\epsilon} = \frac{(346)}{(4.17)\,(0.29)} \\ &= 286 \text{ J/m} \end{aligned}$$

or in more familiar units:

$$\begin{aligned} \frac{E}{L} &= 286 \frac{\text{J}}{\text{m}} \left(\frac{\text{kcal}}{4184 \text{ J}}\right)\left(\frac{10^3 \text{m}}{\text{km}}\right) \\ &= 68.4 \text{ kcal/km} = 110 \text{ kcal/mile} \end{aligned}$$

In summary, it has been shown how conventional methods of thermodynamic analysis may be applied to a living system. The example has been simplified and it is worthwhile to point out some of the refinements which might be introduced. Other variables such as body proportion and training affect the mechanical motion and the thermodynamic efficiency. Other modes of internal work could be considered, such as basal

metabolism and the work performed by the lungs (according to Comroe [3] the power expenditure of the lungs is about 20 watts during running). Fig. 1 and Eqn. (16) are for the case of running at steady state on a hard, flat surface with no wind except that generated by the motion of the runner. Running on hills requires more work because the energy expended climbing a hill is only partially recovered while running downhill. Running against a headwind or running on a spongy surface like wet sand would increase the work of running and alter the stride as well.

HOMEWORK PROBLEMS

In addition to Examples 1-4, there are several interesting thermodynamic problems which can be assigned to enable students to evaluate their own performance during aerobic running:

PROBLEM 1. Plot the energy expenditure of running per unit distance for yourself in units of kcal/mile versus velocity.

Ans. Eqn. (16) applies. Fig. 2 is a plot of this equation for several values of mass.

PROBLEM 2. It is sometimes said that it is cheaper to go by foot than by car. Examine this assumption by comparing the fuel cost (food) for running with the fuel cost for traveling by car (one passenger), for equal distances.

Ans. The cost of food prepared at home is about ten times the cost of gasoline on the basis of equal mass. Assuming reasonable mileages of 5 miles per pound of gasoline (car) and 20 miles per pound of food (person), the cost of running a given distance is more than twice the cost of traveling by car. Of course this calculation ignores capital investment.

PROBLEM 3. Determine the length of your stride and its frequency as a function of velocity for running.

Ans. The result can be estimated using Fig. 1 (see Example 1) and checked by timing the velocity and counting the steps on a measured distance.

PROBLEM 4. What is your mechanical power requirement for running, in units of watts as a function of speed?

Ans. Eqn. (15) applies.

PROBLEM 5. How far must you run at the reasonable jogging speed of one mile in eight minutes to trim off one pound of fat? The heat of combustion of fat is 9 kcal/g.

. . . it has been shown how conventional methods of thermodynamic analysis may be applied to a living system. The example has been simplified and it is worthwhile to point out some of the refinements which might be introduced.

Ans. The energy cost per unit distance is given by Eqn. (16). The required distance is about 40 miles for a person of 70 kg mass.

PROBLEM 6. Calculate your power-to-mass ratio for running in units of ml of oxygen (STP) per kilogram per minute. First find your maximum velocity for aerobic running by finding how far you can run in 12 minutes. This is the Cooper fitness test. Find the mechanical power for running at this velocity using Eqn. (15) and divide this power by the efficiency (0.29) to obtain the rate of combustion. Divide again by your body mass and then calculate your maximum oxygen capacity using the equivalency of 4.8 calories per ml of oxygen.

Ans. See Example 2 for a brief discussion of oxygen capacity.

PROBLEM 7. The dimensionless energy expenditure for aerobic running is

$$W^*/\epsilon = (0.107)/(0.29) = 0.37$$

Compare this figure to that for a compact car.

Ans. For a 1000 kg compact car which uses 6 liters of gasoline per 100 km, the dimensionless energy expenditure is 0.2 (heat of combustion of gasoline = 11 kcal/g) or about half the value for running. For a larger car the dimensionless energy expenditure (0.3 to 0.4) is about the same as for running.

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Continued on page 48.

ChE class and home problems

The object of this column is to enhance our readers' collection of interesting and novel problems in Chemical Engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class or in a new light or that can be assigned as a novel home problem are requested as well as those that are more traditional in nature that elucidate difficult concepts. Please submit them to Professor H. Scot Fogler, ChE Department, University of Michigan, Ann Arbor, MI 48109.

THE DOLPHIN PROBLEM

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WHALES, DOLPHINS AND PORPOISES are able to maintain surprisingly high body temperatures even though they are immersed continuously in cold, cold water. As can be seen from Figure 1, the extremities of these animals (tails, fins, flukes) have a large surface to volume ratio, and a large portion of the heat loss occurs there. Now an ordinary engineering junior designing a dolphin from first principles would probably view the heat loss from a flipper somewhat as shown in Figure 2.

Let us suppose that blood at 40°C enters the flipper at 0.3 kg/s, feeds the flipper, is cooled somewhat, and then returns to the main part of the body. The dolphin swims in 4°C water, the overall heat transfer coefficient is 100 cal/s·m²·K and the area of the flipper is 3 m².

a) At what temperature does the blood reenter the main part of the body of the dolphin?

Frankly, an ordinary engineer (which you obviously are not) would design a lousy dolphin. Let's try to do better; in fact, let us try to learn from nature. Let us see if we can reduce some of the undesirable heat loss by transferring heat

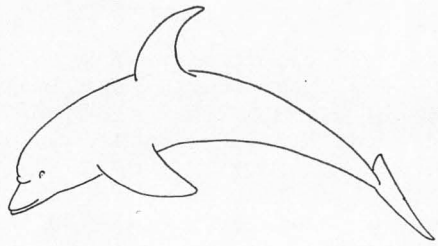


FIGURE 1

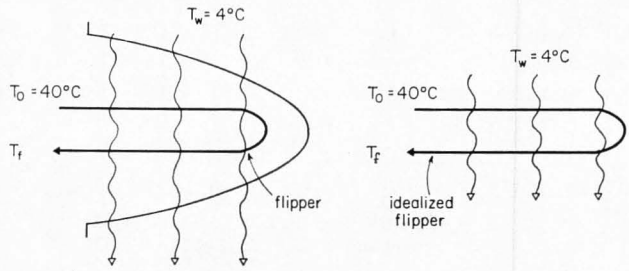


FIGURE 2

from the outgoing warm arterial blood to the cooled venous blood. Such a scheme is idealized as shown in Figure 3. Assume for this internal exchanger B that

$$A_B = 2\ m^2$$

and

$$U_B = 150\ cal/s{\cdot}m^2{\cdot}K$$

b) With this extra exchanger find T_3, the temperature of blood returning to the main part of the body; and, in addition, the fraction of original heat loss which is saved. Approximate the properties of blood by water.

NOTE: Heat conservation of this sort, by having arteries and veins closely paralleling each other, in counterflow, is one of nature's clever tricks.

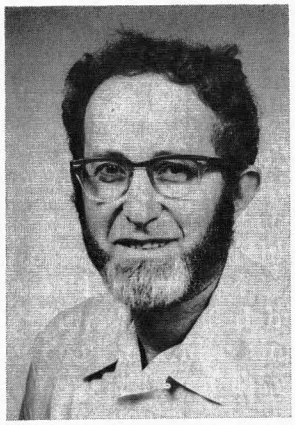
SOLUTION

a) Flipper alone

First, a plot of temperature of blood and water on a q vs T diagram (see Figure 4) gives straight lines meaning that the log mean ΔT is the proper driving force for this process. A heat balance then gives

(heat lost by blood) = (heat transfer rate)

In symbols



Octave Levenspiel, professor at OSU, is primarily interested in problems of chemical reactors. He has written a text on this subject, and has won the ASEE Lectureship Award for his early visions in this field. His weakness for scientific curiosities has led to flirtations with 4-colorologers, 2nd law repealers, Fibonacciics, boomerologists, topolographers, and other such. He is also 1975 president of the Northwest Neothermo Society.

$$\dot{m}C_p\,(T_o - T_f) = UA\frac{(T_o - T_w) - (T_f - T_w)}{ln\,\dfrac{T_o - T_w}{T_f - T_w}} \qquad \text{(i)}$$

Rearranging gives

$$T_f = T_w + (T_o - T_w)\,\exp\!-\!\left(\frac{UA}{\dot{m}C_p}\right)$$

and on replacing values

$$T_f = 4 + 36e^{-1} = 17°C \qquad \text{(a)}$$

b) Flipper Plus Exchanger

Here we must make heat balances about both units to solve for the unknown temperatures T_1, T_2 and T_3. So for the internal exchanger B we have

$$\begin{pmatrix}\text{heat lost}\\ \text{by hot}\\ \text{blood}\end{pmatrix} = \begin{pmatrix}\text{heat}\\ \text{gained by}\\ \text{cold blood}\end{pmatrix} = \begin{pmatrix}\text{heat}\\ \text{transfer}\\ \text{rate}\end{pmatrix}$$

In symbols

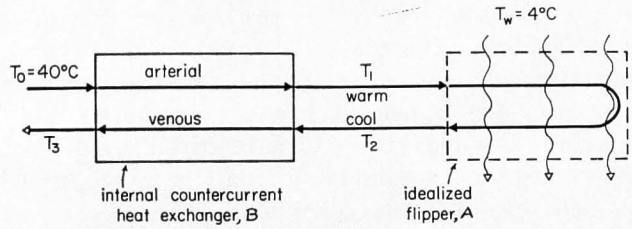


FIGURE 3

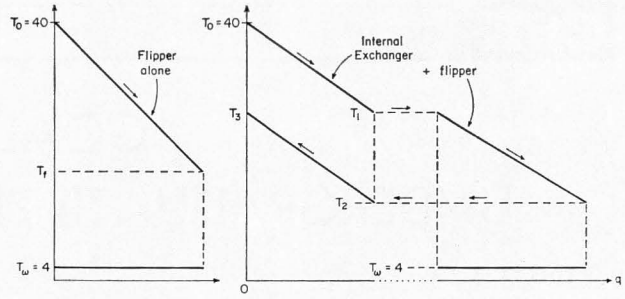


FIGURE 4

$$\underset{\text{I}}{\dot{m}C_p\,(T_o - T_1)} = \underset{\text{II}}{\dot{m}C_p\,(T_3 - T_2)} = \underset{\text{III}}{[UA\,\Delta T_{lm}]_B} \qquad \text{(ii)}$$

For the flipper alone, i.e. exchanger A, we obtain, as with Eq. (i)

$$\dot{m}C_p\,(T_1 - T_2) = UA\,\frac{(T_1 - T_w) - (T_2 - T_w)}{ln\,\dfrac{T_1 - T_w}{T_2 - T_w}} \qquad \text{(iii)}$$

Solving (ii) and (iii) simultaneously gives the unknown temperatures T_1, T_2 and T_3. All else is known. The first step in this solution is to combine I and II to give

$$40 - T_3 = T_1 - T_2 = \Delta T$$

This expression shows that the driving force is the same at both ends of the internal exchanger B. Consequently we should use the arithmetic ΔT, not the log mean ΔT in Eq. (ii). This fact is shown in the q vs T diagram of Fig. 4. The rest is straightforward, giving

$$\text{For Eq. (i)}: 40 - T_1 = T_3 - T_2 = T_1 - T_2$$

$$\text{For Eq. (ii)}: ln\,\frac{T_1 - 4}{T_2 - 4} = 1$$

From which

$$T_1 = 26°C, \qquad T_2 = 12°C, \qquad T_3 = 26°C \qquad \text{(b)}$$

This modification represents a heat savings of

$$\frac{26 - 17}{40 - 17} = 39\% \qquad \text{(b)}$$

EDITOR'S NOTE: Professor Levenspiel's problem statement was published in the 1981 fall issue of CEE. At that time we issued an invitation to our student readers to submit solutions. We congratulate Mike Glass, Washington Univ. (St. Louis) who has submitted the first correct solution and in so doing has won a subscription to CEE.

GOALS OF AN UNDERGRADUATE PLANT DESIGN COURSE*

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PLANT DESIGN IS A PROCESS involving many different aspects, all of which are critical if a profitable product is to be produced. The purpose of an undergraduate chemical engineering plant design course is to acquaint the student with all the myriad aspects of the design process and to give them a feel for process design and its evaluation. It is important in this course to illustrate the difference between the scientific approach and engineering approach to a problem. The scientist will tell you what additional studies must be done or information obtained before an answer can be obtained. The engineer will, from a paucity of data, give an approximate answer and then tell you what must be done to improve upon it or verify it. It is also important to show that there are many adequate designs for any given product. Usually it will never be known which design is best since only one plant will be built and the engineers will do whatever is necessary to make it work. This is the place to wean the student from the concept that every problem has one and only one right answer. In fact some accreditors have insinuated that the essential difference between analysis and design is the difference between single answer and multiple answer problems.

The design course at Ohio lasts two quarters (20 weeks) and is a four hour credit course (each quarter). Most of that time is spent on the preliminary chemical engineering plant design of a specific process. The remainder is spent on short design problems and economics.

The purpose of an undergraduate chemical engineering plant design course is to acquaint the student with all the myriad aspects of the design process and to give them a feel for process design . . . it is important in this course to illustrate the difference between the scientific approach and engineering approach to a problem.

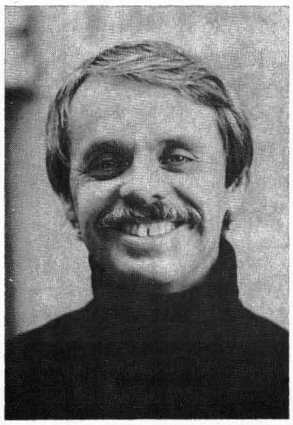
Each year a different process is selected. I always choose a process which the class will be permitted to visit and have an opportunity to discuss with practicing engineers. It is at this meeting with those intimately familiar with the process that the student can have answered all the questions I could not answer in class. (I do not pose as an expert on the plant being designed. However, because I know the process of design and it is that process that I want them to learn, I am qualified to teach the course.) Here they can ask whether some design variation they have proposed is likely to work. Often, whether it will work or not depends on trace quantities of material which may precipitate at those conditions, or on whether an acid may be formed. These are things which a designer may fail to consider and which require process modification after startup. They are the things the university instructor cannot be expected to be familiar with and which often do not appear in the literature. This is what makes design an art.

The capacity I choose for the students' design is usually the same as the nominal capacity of the plant we will visit. This allows them to visually compare their calculated results with actual ones when the plant trip occurs. The benefits of this type of feedback are great. A person must be present during the plant tour to appreciate it.

Since the students will design only one type of plant, the plant trip is expanded into a three day event and we visit an average of six facilities. To prepare the students for this trip each of these plants is discussed from a process design standpoint prior to the visit. The trip, besides being educational, is also fun, promotes class cohesion and provides a needed break in a very rough quarter. The plant trip is a required portion of the course and one hour of credit is given for it.

The only information given to the class about

*Paper presented at the 1979 Annual Conference of ASEE.



William D. Baasel is a Professor of Chemical Engineering at Ohio University. His Bachelor's and Master's degrees were obtained from Northwestern University and his Doctorate from Cornell University. He is the author of "Preliminary Chemical Engineering Plant Design," Elsevier, 1976. He is currently Chairman of the Chemical Engineering Division of ASEE. He had a Ford Foundation Residency at the Dow Chemical Company and spent 1978-80 with the United States Environmental Protection Agency.

the plant they will design is the product, the type of process to be used, and the nominal capacity of the plant. Everything else must be obtained from a search of the literature by the students. (Prior to the first class period I place on reserve all books related to the process which are available in the library. This gives all groups equal access to the volumes.) This brings the student into direct contact with the literature they will need in the future and it points out that finding information is often more difficult than performing calculations. As a result they learn that they can obtain estimates even when critical data are missing; very valuable experience because they will need to do this in the real world. My experience at both Dow and EPA is that many times the engineer will be called upon to obtain answers with no more information than the average student group obtains from the literature.

The students work in groups of three. Nearly every week they complete a written group report on a portion of the design. The sequence repeated below follows the chapters of my text [1] and their reports are similar to those presented there in the case study:

- **Background Report on the Process (2 weeks allowed)**
- **Site Selection**
- **Scope**
- **Unit Ratio Material Balance and Flow Diagram**
- **Major Equipment Specifications**
- **Plant Layout**
- **Instrumentation**
- **Energy Balance and Pumping Sizing**
- **Energy Equipment Sizing and Manpower Requirements**
- **Pollution Abatement Equipment Sizing**
- **Cost Estimation**
- **Economic Evaluation**

The plant trip usually takes place around the time of the instrumentation report. Ideally it would be a week or two later but a plant trip in mid or late November may encounter bad weather and safety considerations rule against it taking place then.

Working together in groups is a valuable experience for the students. This is one of the few times where their grade is very dependent upon how well the group cooperates. Plant design is usually too time consuming for one person to do it all. Even when this is possible and actually done, it is very annoying for the student doing the work to realize that two other individuals received a high grade solely because of his or her efforts. Still more annoying to other groups can be the feeling that their group received a low grade because one member of the group shirked his duty.

These group experiences are simulations of the types the student will encounter in industry and government . . . working in groups also promotes learning. In this situation the student is in an active rather than passive mode.

I encourage the students to see me if they are having personal problems within their groups. A number of times students have taken me up on this offer. It usually occurs because a student is not pulling his own weight. In this case I meet with the whole group and we decide what should be done. The usual result is that the student not working receives a lower grade on the group work than the others.

These group experiences are simulations of the types the student will encounter in industry and government and this introduction to group dynamics is very important. Much of their professional life will be spent working with others and getting others to work with them.

Working in groups also promotes learning. In this situation the student is in an active rather than a passive mode. He is taking part in the direction of the project. Others will criticize his ideas and he will have to defend them. It permits him to see how the others approach problems. Pedagogically, being in an active mode with ones

Each week two hours of class time are devoted to oral reports . . . At this time two groups give a report on their progress for the week.

peers is an excellent way of learning.

At times I have let the students choose their groups. However this often has an adverse effect on minorities, like women and foreign students. The best overall result seems to occur when the faculty member selects the members of the group.

Each week two hours of class time are devoted to oral reports by the students. At this time two groups give a report on their progress for that week. There are a number of reasons for requiring oral reports. One is, of course, to give them experience giving reports. A second is to illustrate that there are design possibilities which most groups didn't consider. A third is to point out problems that might arise if certain approaches are used. Last, it is an excellent place to point out erroneous assumptions and incorrect calculation procedures and to correct mistaken impressions. It is an excellent time to reinforce the concepts presented in unit operations, kinetics, automatic control, thermodynamics and other courses. Forcing the student to express these is an excellent reinforcement of basic principles and can firmly place them in a student's mind. It should be a major secondary goal of all plant design courses.

To aid the students in improving their presentations, one of their oral presentations is videotaped. Immediately after the class this tape is played back for them and they can then note any mannerisms which are distracting or annoying. Generally, no comments from me are required. Their strengths and weaknesses are obvious.

Because all the students are involved in the design of the same process, their oral reports to the class are potentially more interesting to other class members than the usual student reports. To encourage active discussion rather than passive listening I give the students two bonus grade points for each oral presentation session in which they enter into the discussion. (The written reports are graded on a twelve point scale.) I encourage those students who are shy or have difficulty speaking to prepare statements in advance so they get accustomed to speaking.

As another experience in group dynamics, instead of giving oral reports for the site selection topic, the students spend the class time selecting the best site. Each group is charged with coming up with a specific site in advance of the meeting and the class is then charged with picking a site before they leave the classroom. No directions are given as to how this should be done. They are told, however, that the site they select will be their plant location henceforth. After this meeting I discuss group dynamics and how it can affect decisions. I also discuss sensitivity training and how it was once used as a management training tool.

In addition to the time for oral presentations by groups, the class meets two or three times a week. During this time I answer questions, discuss problems that arise, give encouragement, lecture on topics not covered by the text, and expand on topics presented. Some of the topics presented are:

a) **Design of Plants to be Visited during Plant Trip**
b) **Future Energy Availability**
c) **Siting Plants in Foreign Countries**
d) **Steady State Economics**
e) **The World Scene and the Chemical Engineer**
f) **Predicting the Future**
g) **Pollution Abatement**
h) **Environmental Assessments (to be added in the future)**
i) **Safety**
j) **CPM and PERT**
k) **Specification Sheets and General Specifications**
l) **OSHA and EPA Rules**
m) **International Economics**
n) **Instrumentation**
o) **Startup**
p) **Piping and Instrument Diagrams**
q) **Things That can go Wrong**
r) **Risk Analysis**
s) **Socioeconomics**

Since no engineering economics is required as a prerequisite for this course, about three weeks is devoted to this topic. During these periods most of the class time is spent discussing the problems assigned. A test is given at the end of this portion of the course. It counts the equivalent of three reports. Grades are based on the weekly written group reports, the economics examination and the student's individual oral participation. No examinations are given other than the one in economics.

One of the major problems with this course is that it is very time consuming, both for the student and the faculty member. The student learns that he must plan his time or he will never finish. He is expected to do something which would take a professional engineer more time than he

has available. I have tried to consider options as to how to reduce the time that they, and I, spend on the course. However, everything I have considered would significantly reduce the learning experiences of the students.

Short problems certainly could reduce grading time since graduate students could do the grading. However, they do not show how every decision made in the scope affects the result. They don't illustrate the interrelation of all parts of the design. By failing here they don't succeed in illustrating the total process of design. They are often single answer problems. They usually tend to be nothing but extensions of the types of problems given in other courses. There is also a tendency of short problems to provide the students with all the required information rather than forcing them to find most of it. This will not prepare the student for the vaguely defined problem with little or no data which he will confront in industry or government.

Some instructors feel time may be saved by using a computer program to do routine calculations. This certainly is true in industry where numerous calculations of the same kind are frequently repeated. However, before any computer program is used, all the assumptions must be understood so the program is not misused, and the format for entering data into the computer must be learned. Each of these takes time. The former takes the most time. Since most calculations are not repeated very often and various good sources of quick estimates are available [1, 2, 3] it does not appear that any time is saved. The potential loss is that the student doesn't have to review previous course material. Students will very happily plug into programs without trying to understand them. This prevents them from achieving one of my secondary goals, reviewing previous course material. They will also happily spend hours manipulating the programs. This time could be more profitably spent elsewhere.

With computers a more accurate, consistent design will result. It will be much easier to make changes, to perform numerous sensitivity analyses, and to optimize the design. None of these, however, are goals for my course. It is important for students to understand that these tasks can be done; however it is not necessary this be done in the context of the total plant design. These goals can be achieved just as well with simpler examples where the concepts do not appear as mysterious.

In summary, the major goal of the course is to give the student an understanding of the process called plant design. This is done by having the student perform a plant design and by completing the design the student shows he has obtained this understanding.

In addition to the major goal there are also many important secondary goals. These are:

- **Learning to work with others.**
- **Improving report writing.**
- **Improving oral presentations.**
- **Learning to find what is available in the chemical engineering literature.**
- **Learning to obtain answers when little data are available.**
- **Correcting mistaken concepts.**
- **Reinforcing course material to which they have been previously exposed.**
- **Learning there is more than one way to approach a problem and there usually is more than one solution.** □

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ChE book reviews

LABORATORY ENGINEERING AND MANIPULATIONS

By E. S. Perry and A. Weissberger
John Wiley, 1979

Reviewed by John R. Hallman
Nashville State Technical Institute

For the individual who has acquired a chemical (2-year associate) degree (engineering oriented), the chemical engineering technician or the graduate chemist with mechanical ability, this book would serve well in the intended use. However, for the chemist who is not mechanically oriented, usage would be limited; but with careful study the latter person could use the material in

Continued on page 41.

ChE design

DEVELOPMENT AND CRITIQUE OF THE CONTEMPORARY SENIOR DESIGN COURSE*

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SENIOR DESIGN COURSES VARY far more from school to school than any others in the chemical engineering curriculum. The particular form of a given course seems to depend mainly on

- **the tradition in a department**
- **the goals of the instructor or staff**
- **the degree of faculty participation**
- **the availability of resources**
- **the instructor's experience or background**

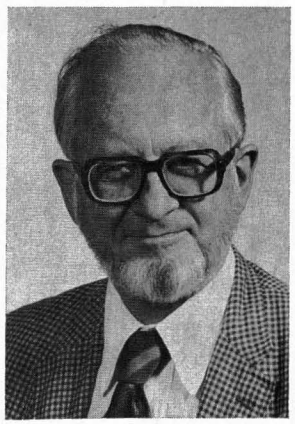
In view of the spectrum represented by the design course as offered across the U.S., a careful and orderly consideration of its many aspects has been made as a way to clarify its goals and to point out ways to improve this course.

RATIONALE FOR THE DESIGN COURSE

THERE HAS BEEN A STRONG consensus, almost unanimous, among chemical engineering educators, that a major design exercise represents an essential element of the curriculum. Common justifications for this position are:

- **an integrating experience—a course in which the students draw on and use their wide and varied resources**
- **an opportunity for the creative application of theoretical fundamentals to practical problems**
- **an exposure to the real world of engineering; in particular the handling of open-ended problems**
- **an exercise in organizing and completing a complex project**
- **the introduction and/or use of economics in the decision-making process as a vital and central factor in design.**

*Based on a paper presented at the 72nd Annual Meeting of AIChE, San Francisco, November 1979.



Vincent W. Uhl received his degrees in chemical engineering at Drexel and Lehigh. He has worked for Sun Oil, Downingtown Iron Works, and the Bethlehem Corporation where he was manager of the Process Equipment Division, 1951-57. He has taught at Lehigh, Villanova, Drexel, and Virginia, where he arrived as Chairman in 1963. He is co-editor of MIXING: THEORY AND PRACTICE (2 Vol.). In 1977 he was elected a FELLOW of AIChE. He has served the Chemical Engineering Division of ASEE as both a member of the executive committee and as chairman (1977-78).

DEVELOPMENT OF THE SENIOR DESIGN PROJECT

THE EVOLUTION OF THIS course can well be traced in terms of the content and emphasis of the design texts used by U.S. schools over the past forty years. It can be considered to have taken place in five stages which overlap to some extent.

1. **Preliminary engineering along with process calculations was emphasized; this preliminary engineering was concerned with items such as simple foundations, and service facilities. See three editions of Vilbrandt [1].**
2. **The engineering calculations become concerned almost exclusively with the process design. And at the same time projects of some complexity were regularly undertaken. Both these trends are demonstrated in Vilbrandt and Dryden [2], and Baasel [3].**
3. **Engineering cost analysis, and sometimes optimization, were formally made a regular part of the project; this is especially emphasized by Peters and**

Timmerhaus [4, 5]; it is also demonstrated by Baasel [3], Sherwood [6], and Bodman [7].

4. Rules of process synthesis as elucidated by Rudd et al. [8], and Motard and Westerberg [9] are used. They serve to codify good engineering practice, and both facilitate and optimize the selection of necessary process steps.
5. The use of computer programs was introduced for process design and also, in some cases, for engineering cost analysis. Examples of such program are: FLOWTRAN, CHESS, CHEMOS [10].

For this development the rationale declared above was fully realized by the third stage, i.e., the economic evaluation of preliminary process designs for complex projects (this corresponds to systems engineering), and the ability to solve open-ended problems (this is considered to be the application of the practice of engineering.) The fourth and fifth stages are concerned with sophisticated techniques which, in recent years, have often become the *raison de etre*, and thereby have often served to obscure the basic goals of the design course. The primary goal of the senior design project should not be the teaching of special techniques or even process design *per se*. Rather it is a means to an end: an experience in the practice of engineering. Fortunately the field of chemical engineering provides excellent tasks for realizing the stated general purposes of the design course. In contrast, other engineering disciplines appear to lack manageable vehicles that are as complex; projects are generally restricted to only elements of a system: structures, machines, and devices.

The purposes of a curriculum are best served by recognizing the stated basic goal of a senior design course, and then providing opportunities for students to organize and complete complex, open-ended problems. Sophisticated techniques should be explained to demonstrate helpful, available tools, but facility in their use should not be the primary end.

NATURE OF THE ASSIGNMENTS

CHARACTERISTICS COMMON TO THE preponderance of senior design courses are commented on below:

Subject Matter: Processes amenable to chemical engineering type analysis are usually selected; for example, they include wastewater treatment, flue gas desulfurization, food processing, artificial kidney system, and the processing of nuclear waste. The range of possible problem topics is demonstrated by the AIChE Student Contest Problems, and the Washington University Case Study Series in Design [11], Sherwood [6] and Bodman [7].

. . . the rationale . . . was fully realized by the third stage, i.e., the economic evaluation of preliminary process designs for complex projects (this corresponds to systems engineering) and the ability to solve open-ended problems.

Number of Exercises: These vary from comprehensive projects such as the examples cited above, to two or more graded exercises. Statements of suitable short problems can be found in Peters and Timmerhaus [4, 5].

Level of project execution: The conception and level of most projects corresponds to what is termed a preliminary process design. This requires

- **A definition of the process as expressed by a process flow diagram, e.g., Baasel [3, p. 262], Vilbrandt and Dryden [2, p. 65], Sherwood [6, p. 9]**
- **Mass and energy balances. The results can be effectively presented on flow diagrams, e.g., Vilbrandt and Dryden [2, pp. 65, 67]**
- **Sizing of major pieces of equipment for the battery-limits process**
- **An engineering cost analysis**
- **Sometimes, a process control scheme**

The sizing of lines (piping) is not usually included, also, ancillary facilities are specified for the scope, but not designed or sized. The capital cost for the battery-limits plant is usually estimated by a factor times the sum of the delivered cost of the major equipment items.

Format of Completed Report: The design is presented in a report that includes appropriate background, a description of the process, the completed preliminary process design, an engineering cost analysis, comments, conclusions, and in an appendix examples of the calculations. A form is outlined in Peters and Timmerhaus [4, 5], and specified in the instructions for many of the current AIChE Student Contest Problems.

From school to school reports are fairly consistent with respect to format, the range of subject matter, and emphasis on project innovation. The variation occurs in the number and kinds of assigned exercises. Some departments work only one major problem, others consider several shorter exercises, but graded in difficulty; most schools assign at least two projects—often the last is the AIChE Student Contest Problem, to be solved either by a group or by individual students.

EXECUTION OF DESIGN COURSE

ESSENTIAL REQUISITES ARE AN awareness of the goal, appropriate projects, and students who are both adequately prepared and genuinely interested; but the quality of the course depends on its execution. This calls for a sound plan, effective management, and sufficient resources—mainly faculty. Successful execution is assured by following these three basic ground rules:

- **The students should work in groups, at least for the more complex problems. A three-person group is widely held as ideal and two persons are considered satisfactory; with four or five person groups it is commonly observed that one or two persons tend to participate less, if at all.**
- **The progress of the design effort, particularly in the more advanced or final problem, needs to be monitored, reviewed, and discussed in scheduled sessions with the instructor. However, it is desirable that the instructor also be available for a few posted hours each week for impromptu queries. If the counsel is always available, the groups may tend to "lay back" and lose initiative. Because of this kind of interaction, this course is unique—it assumes the character of an internship.**
- **The projects, particularly the major one, should compel the student to "stretch"; that is, to require knowledge and information beyond that drawn from past resources. It should demand that the student learn and gain facility in subject matter on his own, with guidance or tutorials from the instructor only as a last resort.**

If assignments are made, designs undertaken, and reported without the benefit of these three practices, the exercise . . . most often degenerates to a fantasy of "busy work."

The orchestration of this conventional wisdom requires a considerable investment of faculty time. If assignments are made, designs undertaken, and reported without the benefit of these three practices, the exercise (although impressive in terms of the bulk of paper generated) most often degenerates to a fantasy of "busy work." Students can be misled regarding the efficacy of such unguided or undemanding efforts.

Effort of the Teaching Staff: The intelligent use of adequate and competent staff is essential. Assistance from capable persons in industry can be valuable. However, their efforts should be well coordinated. Industry persons are of use as lecturers, but they are of greater value for the combination of advising and grading reports of a few groups. For this they must be on hand at scheduled times (preferably once a week). Experienced teachers agree that graduate students serving as course assistants can contribute little guidance to students, in particular because they lack the background of practice and because of limited experience in their field. By far the most important factor is the effort and competence of the faculty.

Obviously, course instructors should have some process experience—in design, operation, or development. This requirement can be obviated by faculty with an interest in design, and by the use of solved exercises such as the Washington University Case Series in Design [11]. Sufficient staff time and energy is more essential; the intensity of effort is higher than that ordinarily demanded by lecture courses. Also, because fresh problems are assigned each year, the demands correspond to that for a new course preparation. In addition, the conferences with student groups (both scheduled and impromptu) add up to one to two hours per group each week. Because of these considerations, and to retain freshness in the face of tedium generated by too much exertion in this one course, it is fairly well held that one faculty member cannot effectively handle more than about twenty students, or five or six groups. Fair and Smith [11] state: "The manpower commitment . . . to support a really effective, professional process-design course, . . . requires at least twice as much time to teach as an ordinary lecture course." Accordingly, chairmen often have a problem adequately staffing this course. Some faculty avoid making their contribution because the exhausting labor is offset with correspondingly little credit, and it bears no connection to their scholarly activities.

The staffing problem for the design course has become acute with the upsurge in enrollments. Departments are faced with fifty or more seniors instead of the twenty which could be handled by a single faculty member. This has generally meant fewer and larger groups, less advising, and less demanding projects; each of these factors reduces the benefits to students.

Help from Industry: There are two kinds of significant assistance from industry. One is by individuals to a particular school. As mentioned above, this takes the form of lecturing, advising, and grading. If well coordinated with the overall schedule, it can prove significant. Students respond well to lectures and pointers from practi-

The fourth and fifth stages are concerned with sophisticated techniques which, in recent years, have often become the raison de etre, **and thereby have often served to obscure the basic goals of the design course. The primary goal of the senior design project should not be the teaching of special techniques or even process design** per se. **Rather it is a means to an end: an experience in the practice of engineering.**

tioners, who are working "on the line." And their help in advising and grading can be invaluable.

The other form of assistance comes from industrial support of several, well-established, regular programs. Examples are:

- **The preparation and then the evaluation of the AIChE Student Contest Problem.**
- **The preparation and publication of the Washington University Case Series in Design (11)**
- **The preparation of material for the FLOWTRAN program (10).**

These provide a treasury of teaching materials.

Competent assistance from industry should be used whenever it is available, provided that it can be well coordinated with the scheduled program. Such help is much more valuable when it is offered periodically, e.g., once a week, and where the service includes advising several groups of students, and grading design reports.

It must be recognized that the manpower requirement from the regular staff is considerable, and that it varies somewhat with the number of students taking the design course. For a "meaty" course with a reasonable size class (say twenty students), it is considered to take about twice as much effort as teaching a regular lecture course.

THE STUDENTS: PRIOR TRAINING AND ATTITUDE

IT IS COMMONLY ASSUMED that students entering their fourth year in chemical engineering in accredited programs possess the requisite background and motivation to undertake a substantial design project. This implies some proficiency with process calculations. Unfortunately, this appears to be less true today than it was a decade or two ago. The two main reasons seem to be:

1. **Courses intended to develop ability in essential process calculation, e.g., mass and energy balances, often lack the required intensity of effort. The result is that on the average students have less grasp of the fundamentals, and are not sufficiently facile with the elementary computations.**
2. **Currently, many curricula emphasize analysis, sophisticated techniques, and also more credit hours for electives at the expense of a sound understanding of, and facility with, fundamental engineering subject areas.**

Then there is the matter of the attitude of the students. Although the engineering schools are again enjoying large enrollments, with the current "career oriented" attitude there seems to be less will on the part of students (in fact around the world) to expend the intense effort demanded to experience a professional-level education. And in engineering, a design course appears to be critical in this regard. Further, in today's educational milieu, students seem (to some extent) to determine the pace of their education.

The trend in curricula toward too much specialization by courses (too many electives) can be held in check by accreditation standards and visits. However, the vitiation of fundamental courses by inordinate detraction to subsidiary topics and special techniques can proceed undetected.

There seems to be little that the teaching profession can do to obviate the deleterious effects on declining student commitment and interest where it occurs.

THE FUTURE

THIS REVIEW RAISES SEVERAL questions. Is the design course as taught along these established lines in a malaise? Note that it now attempts to include the features most recently published by ECPD [12], namely:

a. **"development of student creativity,**
b. **use of open-ended problems,**
c. **formation of design problem statements and specifications,**
d. **consideration of alternative solutions,**
e. **feasibility considerations, and**
f. **detailed system descriptions."**

However, some change may elicit favorable response and fuller commitment of students. The ECPD document [12], which expresses the desire for design contributions in the curriculum "to include a variety of realistic constraints such as economic factors, safety, reliability, aesthetics, ethics, and social impact" may provide some stimuli. Instructors at some schools have already been taking such suggestions to heart.

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ChE design

THE CHEMICAL ENGINEERING PROCESS DESIGN SEQUENCE AT VIRGINIA TECH..... AND A NEW PERSPECTIVE*

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WHEN I LEFT Virginia Polytechnic Institute and State University (Virginia Tech or VPI&SU) in 1978 to take a position in industry, I wrote the following description of the Process Design Sequence at VPI&SU to record what had been done and to provide some assistance to my successors. To that description, I have added a postscript that reflects my new perspective.

INTRODUCTION AND OVERVIEW

THE PLANT DESIGN AND economics sequence of courses has been, with the unit operations laboratory, an important and distinctive part of the curriculum at VPI&SU. The nine hours offered are somewhat more than are offered in most departments. The style of the sequence has evolved over the years and has reflected both the instructor and the educational conditions prevailing at the time.

The founder of the department, Dr. Vilbrandt, wrote several editions of an important early text on process design [1]. In a paper he wrote describing the course as he taught it, he emphasized the laboratory orientation of the design experience. Students began in the Fall with one or more major projects and worked as teams for the rest of the year. Some examples, found in departmental files, are recovery of zein from corn and production of penicillin. The course met for one hour of lecture and six hours of lab each week all year. The student teams gathered critical data needed for a design by performing experiments in the laboratory. At the same time, the students were each completing a senior thesis.

In addition to being one of the few professional activities that is explicitly taught in school, design is the one course in which students learn to think in a new way, and to synthesize what they have learned . . .

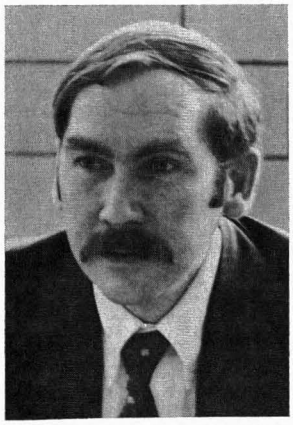
At some point, a course on industrial economics offered by the industrial engineering and operations research (IEOR) department was included in the curriculum and so, presumably, the lectures on design emphasized such matters as equipment sizing and layout. One component of the final reports was a scale model of the proposed plant.

By 1972, the course had evolved into a less integrated sequence but with the same sort of schedule. The Fall quarter had some economics, but the students still took Industrial Engineering Economics. The senior thesis had disappeared, but some students did undergraduate research. It was common to introduce a major design case study late in the Fall and then have groups work most of the Winter on the same case. Several of the cases published by Washington University were used this way, especially one (on cellulose triacetate) that had been developed at VPI&SU in cooperation with Du Pont. Spring quarter was a kind of wrap-up course that was intended to help prepare the seniors for their careers and was not designed to be very demanding, in recognition of Spring fever and senioritis.

When I assumed responsibility for the sequence in 1972, I followed much the same pattern: Fall was a sort of pre-design experience, emphasizing process synthesis; Winter relied on a major case, usually some portion of the cellulose acetate study; and Spring was more specialized, emphasizing simulation, optimization and computers.

About 1975, the curriculum was revised to drop the IEOR economics course on the grounds that chemical engineers needed a different empha-

*Paper presented at ASEE Annual Conference 1979, in Baton Rouge, LA.



J. PETER CLARK received his B.S. in Chemical Engineering from Notre Dame and his Ph.D. from the University of California, Berkeley. He was Assistant and Associate Professor at Virginia Polytechnic Institute and State University from 1972 to 1978. Before that, he spent four years with the U.S. Agricultural Research Service. He is a registered professional engineer in Virginia and a member of AIChE, ACS, ASEE and IFT. He was Director of Research at ITT Continental Baking before becoming President of Epstein Process Engineering.

sis. At the same time, credit for senior seminar was removed and the Monday lecture hour was dedicated to visiting seminar speakers. Don Michelsen, who had a special interest in economics, took over the Fall course and experimented with personalized system of instruction (PSI) using several economics texts. He also tried the idea of using teams of students as consultants to industry. PSI was a mixed success; the team studies were better received. As part of the reorganization, the Winter and Spring courses were combined for six hours in the Winter. This meant that there were no required courses in the Spring, and so the number of early graduations increased.

I divided the new Winter combination into a "group" course and an individual course and treated the six available credits as one course with + or — grades possible. For half the grade, each student did a major project of his choosing; for the other half, he worked on several smaller studies which were assigned by me and often done in groups. In 1978, due to the larger number of students, all students did the AIChE Student Contest Problem as the individual project. Also, in 1977, I inherited the Fall course on economics because Don left the teaching faculty temporarily. The hours were changed to three hours of meeting plus the seminar, and the course became a more conventional lecture course.

Thus, the history of the sequence has been evolutionary. It has yet to be nominated as anyone's favorite, but the complaints about overwork seem to have been satisfied by the combination of the Winter and Spring courses. In 1978, there were at least nine outstanding (in my opinion) entries for the student contest problem; it was hard to select the two that could be submitted. Student teaching evaluations have consistently improved over the years, which may be a reflection of experience, but are yet to reach the highest level. That may reflect the fact that it is a required and difficult course. In general, I feel the course sequence is good for its purpose, but I do not mean to suggest that another way might not be better.

PROCESS ECONOMICS

SO FAR, three texts have been used: Jelen [2], Woods [3], and Peters and Timmerhaus [4]. I planned to use a fourth, Happel and Jordan [5]. In 1977, I chose to lecture to one large section for one hour on Monday and two on Wednesday, rather than repeat the lectures to two smaller groups which would have then met every day.

There were two major objectives: 1) convey the essentials of process economics, especially the measures of worth such as discount cash flow and present worth, along with some information on taxes, depreciation and accounting; and 2) discuss the nature of the chemical industry and chemical engineering careers.

It has been suggested to me, by a professor elsewhere, that doing the contest problem be seen as a privilege urged only on the best prospects while the others do something else, perhaps in groups of two or three.

For the second part, I drew upon ideas from the recent book by Wei and Russell [6]. The students each prepared term papers on one chemical company of their choosing and on one chemical of their choosing. They also did homework problems from Peters and Timmerhaus, but I took the chapters out of order, which, in retrospect, did not work well. I recommend using any text in the order written, as a general rule. I gave one in-class exam and a final. We spent a fair amount of time discussing career opportunities, including graduate school, interview techniques and so forth. The Fall is the time to do this, as recruiting is heaviest then. I demonstrated, using present worth, that the discounted value of cumulative before-tax earnings for a chemical engineer with a Ph.D. was greater (in less than ten years) than that of

one with an M.S. and that his was greater than that of one with a B.S. This elegant proof did not seem to affect any decisions, sad to say.

PROCESS DESIGN

MY PATTERN in the six hour Winter quarter pair of courses became fairly stable. About half of the credit was earned by an individual project and the other half was earned from a collection of assigned group and individual projects. There were no exams or final. I used both individually selected projects and the AIChE student contest problem. My practice was, since 1974, to solve the student contest problem myself over Christmas vacation. For three years, this was merely an enjoyable exercise of my skills; in 1977, it was valuable preparation for the course. Only about the top quarter of the class is really capable of doing a good job on the problem, in the sense of preparing a competitive solution. It has been suggested to me, by a professor elsewhere, that doing the contest problem be seen as a privilege urged only on the best prospects while the others do something else, perhaps in groups of two or three.

Part of me accepts this, while another part is concerned that we might miss some good work from latent stars or that, given the choice, no one will really exert themselves. I have not resolved this problem. I feel that our students have a decent chance in any year at any one of the cash prizes and so would like to have as many as possible make the effort.

The contest problem is always a challenge and I believe few students will attempt it voluntarily or for no credit. Thus, I favor some compulsion to get entries. I also feel that at least once before they graduate, they must stand on their own and do one comprehensive design exercise. The difficulty is that counseling and then grading over fifty such exercises is rather time consuming for one person.

By comparison with other engineering departments, chemical engineering at VPI&SU demanded more of the students, but we also gave more credit. In addition to the individual project, I have had good success with exercises involving outside help. There have been two categories: 1) a novel compound described by a chemist [7], and 2) a project involving someone from industry.

Hamp Smith, from Chemistry, worked with me for three years (more or less in exchange for a lecture by me to his class). He and/or another professor (Jim Wolfe in 1978) came to the class and described some compound they had synthesized. They alone had all the information available on this compound. We created some reason for being interested in the substance, (Wolfe had a potential anti-epileptic drug). Groups of students were assigned the problem of designing and estimating the cost of a plant to make some large quantity of the compound, say several million pounds. The chemists were very cooperative and the students seem to like the exercise. Ideally, it should come late in the course, after some other practice, but not so late that it conflicts with the individual project, which they inevitably put off until late.

The other class of project was mainly an excuse to get an industrialist into the class. In past years I had help from Lannie Robbins of Dow (recovery of acetic acid), Al Conner of UOP (catalytic cracking), Keith Baugher of Exxon (cat cracking), and Bob Bickling of Du Pont (cellulose acetate). I usually presented an agreed-upon case to the class and let them struggle for a while. Then the visitor came to serve as a consultant and critic. I graded the reports. The students liked these exercises. The key here is planning for the best use of such help. Unfortunately, it does not relieve the grading load, which is the major time demand.

Another class of exercise which has been successful, usually at the first of the quarter, involves the past student contest, whose solution is published in the Fall Student Members Bulletin from AIChE. I usually ordered about 70-100 of these as student chapter counselor. In my experience, there is always something that can be improved upon in the winning solution. I assigned the problem of finding an alternative solution, correcting (or at least checking) the solution or some other excuse for reading the winning report very carefully. This, I hoped, would create some sympathy for my difficulties in reading their own reports and it may have convinced them that it was not that hard to excel in the contest.

Whatever the first assignment may have been, I announced after it was turned in that it would not affect their grade, but I criticized it as if it would. This gave them a feel for my standards and it gave me a measure for whatever improvement may result from the course. In past years, I felt that the improvement was significant, which was gratifying.

Other exercises I have used over the years have

come from various sources, such as the cases published by AIChE under Jud King, Sherwood's book [8], my own experiences, and articles in CEP. I tried to have about five or six graded exercises.

For a text, I have used both Peters and Timmerhaus and Baasel [9]. Jim Douglas has a new book in manuscript which I reviewed in part for a publisher. It looks promising, but has not yet appeared. Peters and Timmerhaus is being revised but will not be out in a new edition until 1980; right now, I feel it is out of date and that the combination of Happel and Jordan with Baasel is better.

I found an entertaining way of forming groups. I selected the appropriate number of people, say 15 if I wanted 4 person groups in a class of 60. The first time I selected people whose combination I felt would provide an unfair advantage, i.e. some of the better students; but I usually included some "sleepers"—people I felt needed some leadership experience. We retired to another room and held a draft, using the roll sheet. The last to pick on the first round got the first pick on the second round to make things more equitable. I determined the order of picks more or less arbitrarily. It was most informative to learn who in the class got picked in what order. On the next group project, I either kept the same leaders but allowed them to "protect" only one of their group, the rest becoming available to the draft, or I chose new leaders. There is usually a chance to do both during the year. The student evaluations of their peers were most useful to me and usually conformed with my own assessment once the grades were computed. Sometimes the students learned some valuable lessons also; one year, the last man picked on the first round was protected on the second round.

The substantive material of the Winter course is well described in my little series of articles in *Chemtech* [10]. Most of class time was spent discussing the current case, but somewhere during the course, I tried to cover the essentials of design as I saw them. There was a very heavy emphasis upon good writing, neat flow sheets, accurate material balances, clear and correct economic estimates, and good judgment. I found that estimation of physical properties was always a need, as was proper citation of references in reports.

As the title of my article suggests, I emphasized preliminary design, as do Baasel and Douglas, which is why I like their books. This means teaching a kind of creative sloppiness, which is foreign to the student after the relative rigor of his junior year courses. There is a proper place for rigor, of course, as there is for computer-aided design, which is also an interest of mine but which I did not emphasize in the course. I tried to have the students do at least a few tedious calculations of non-linear material balances or adiabatic flashes so they would appreciate what the computer could do for them. However, it wasn't convenient or practical to have the class use FLOWTRAN or CHESS in the past. Another instructor might find a way; certainly, many in other schools do [11].

I did have a good experience with a small business game taken from *Chemical Engineering Education* [12]. One student developed the code for the Department's PDP-11/40 and the other students competed in groups.

The resources available to assist an instructor of process design are limited only by his imagination [13]. There are over 20 cases from Washington University, 14 from the King project with AIChE, and about 46 past student contest problems from AIChE. Only a handful of these resources are needed to get through the year. I have developed some others of my own, but so can anyone who wishes to do so.

POSTSCRIPT

As an employer of chemical engineers in industrial research and development, I now see the process design sequence differently than when I taught it.

We do very little process design in the sense that most courses discuss the topic or in the sense that design firms or groups actually practice the trade. Probably, that is true for many chemical engineers employed in operations, research or technical service. Is design then irrelevant to us? Far from it!

In addition to being one of the few professional activities that is explicitly taught in school, design is the one course in which students learn to think in a new way, and to synthesize what they have learned elsewhere. These are critical skills in any career, as many people agree. I also feel that a good design experience helps convert students into engineers by convincing them that they actually can perform competently and relatively independently in the face of pressures and the challenge of more ill-defined problems

Continued on page 42.

AN EXPERIENTIAL DESIGN COURSE IN GROUPS*

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IN LOOKING TO THE FUTURE of engineering education, Dr. Lee Harrisberger [1], past president of the American Society for Engineering Education, predicts that one characteristic of the 1990 university will be a dual curriculum. The first segment of the curriculum is predicted to be based on skills, which includes knowledge, comprehension, and application to closed ended problems, while the second segment is predicted to be competency based, including problem analysis, synthesis of skills previously learned, and evaluation as applied to real-world problems. The Accreditation Board for Engineering and Technology currently recognizes the need for competency courses by requiring one-half year of engineering design in the undergraduate curriculum for accreditation. The experiential, or "learning by doing" courses are most often found in chemical engineering curricula in the unit operations laboratory and in a capstone senior design course.

If an objective of a senior design course is to simulate industrial experience by teaching open ended problem solving, the professor may be required to teach differently than in the normal undergraduate class. While the professor may normally build on his past teaching and problem solving experience in a course like kinetics, each design class requires that a new problem be addressed. Further, if an available case study is used in design, the assumption is made that the students will not obtain a different or better solution than that available. Case studies are very useful teaching tools, but they remove some of the open ended flavor in design.

If an objective of a senior design course is to simulate industrial experience by teaching open ended problem solving, the professor may be required to teach differently than in the normal undergraduate class.

Students also must behave differently in such a design course. In addition to the creative, open ended aspects of the course, the students must communicate well and work in groups. In most cases, the groups are self selected and tend to be composed of friends with harmonious personalities. Such a group composition is considered neither ideal for problem solving nor indicative of real-world problem solving groups. Students should learn to work with different personalities in a constructive manner.

COURSE STRUCTURE

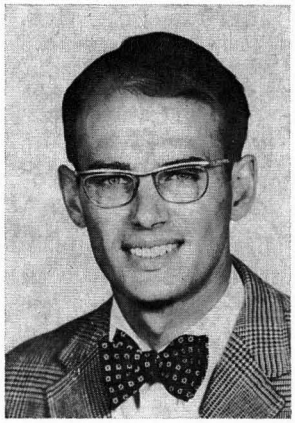
THE PRIMARY GOALS OF the course are to provide an authentic design experience, to increase interpersonal awareness, and to increase communication skills for students. The course is divided into three segments as follows:

1. **an introduction to the design, decision-making process (two weeks),**
2. **an introduction to group dynamics and personality typing (two weeks), and**

TABLE I
Steps in the Design Decision-Making Process

GUIDED DESIGN	THE UNIVERSAL TRAVELER
1. Identify the Problem	1. Accept the Problem
2. State the Basic Problem	2. Analyze the Facts
3. State the Constraints and Assumptions	3. Define the Problem
4. Generate Possible Solutions	4. Ideate for Solutions
5. Evaluate and Choose Likely Solution	5. Select Solution
6. Analysis of Solution Components	6. Implement Solution
7. Synthesis to Create Detailed Solution	7. Evaluate Solution
8. Evaluate the Solution	
9. Report and Recommend	
10. Implement the Decision	
11. Check the Results	

*Paper presented at ASEE Annual Conference 1979.



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3. the design of industrial projects provided by companies in the Golden-Denver area (eleven weeks).

Each of the portions of the course are described below.

Initially, the students are introduced to three types of design, i.e., preliminary designs, detailed estimate designs, and firm process design, through a standard text by Peters and Timmerhaus [2]. Two supplemental texts, Guided Design [3] and the Universal Traveler [4] are used to study the individual components of the design decision-making process, as shown in Table I. Each of four years of the Wright brothers' design process [5] is studied to evaluate how these classical engineers resolved their design problems using the above procedure.

The group dynamics portion of the course is done with the help of a consulting psychologist. Each student voluntarily takes the Myers-Briggs Type Indicator (MBTI) [6], a written, multiple choice personality indicator based on Jungian principles. The thirty-five year data history of the test provides a basis for personality typing into the following four categories:

- **the method of gathering information (by senses or intuition)**
- **the method of making decisions (by thinking or feeling)**
- **the preference for gathering information or making decisions (perceptive or judgemental)**
- **the preference for dealing with the outer world (introversion or extraversion)**

The implication of using the MBTI in normal engineering teaching situations have been addressed elsewhere [7]. Here, the results of the MBTI allow the students to be divided into small groups which are not only equivalent on the bases of past grades, but also contain as many diverse personality types as possible. The students voluntarily share their personality types with the others of their group, and each group discusses how the individual types might interact in the forthcoming design project. Group effectiveness exercises are done using materials provided by Dr. Lee Harrisberger [8].

During the final eleven weeks of the course, each group performs an industrial design, chosen jointly by second level company supervision and the professor. Each project deals with a real industrial problem which has not been solved by the company. Typical projects during the last two years are listed in Table II. Every week during the

From the professor's standpoint, this type of course has several [additional] . . . benefits . . . The students view the professor as a resource, not an adversary, to accomplishing the design project.

TABLE II
Chemical Engineering Design Projects

COMPANY	PROJECT
1. Union Carbide	Removal of Isopropanol and Isopropyl Ether from a Brine Liquid Stream
2. Union Carbide	Recovery of Isopropanol and Isopropyl Ether from a Vapor
3. CSM Research Institute (CSMRI)	Modeling Methods of Ethanol Production
4. CSMRI	Pilot Plant Design for Coal Gasification Process
5. Earth Sciences	Production of Fluoride Salts from Fluosilicic Acid
6. Hazen Research	Hydrogen Reduction of Lead Concentrates
7. Hazen Research	Flue Gas Desulfurization
8. Solar Energy Research Institute	Olefins from Solid Waste
9. Adolph Coors	Use for Waste Steam

project phase of the course, each group is allowed an interaction (conference call or site visit) with an engineer of the company involved. The groups interact with their company in the same way any process/project group would interface with the user of a design effort. The needs for additional information for integration of solutions into existing processes, intelligible historical information, the continuing development of new operating data, etc., make each problem more difficult, but very realistic.

At the conclusion of the project each group provides the company engineer with an engineering log book as a record of all calculations, problem solving sessions, company interactions, and vendor quotes. The second level management of the company is also provided a formal written report, mid-term oral report and a final oral presentation.

CASE STUDY OF A DESIGN PROJECT

DURING THE FALL SEMESTER of 1980 the Adolph Coors Company requested that the design class assess how best to use the wasted energy from the brewery's electrical power generation turbines. After all of Coor's internal energy needs were met, the company was exhausting 175,000 lb/hr of steam to the environment, with a future exhaust of 550,000 lb/hr as the plant reaches maturity. In return for the study, Coors gave a $5,000.00 grant to the Chemical Engineering Department, which was used as student financial aid.

After several weeks of considering alternatives in a typical problem solving mode, the students determined that the object of the design should be to complete a feasibility study of using the waste heat for district heating in Golden, Colorado. Preliminary investigation indicated that virtually all of the houses within a one mile radius of the Coor's brewery could be heated with the waste energy.

The study included four major items as follows: 1) a market analysis, 2) the design of a cogeneration heating and distribution system, 3) a capital cost estimate, and 4) a financial sensitivity analysis.

Similar studies by the Electric Power Research Institute, the Oak Ridge National Laboratory, and Swedish and Danish companies were evaluated. The students also obtained the help of professionals at the Public Service Company of Colorado, the nearby Solar Energy Research Institute, and the Golden City Engineer's Office. The students were fortunate to have a fine, young Coors engineer, Mr. Sam Baxter, to assist them in their application of principles. Among the engineering principles used in the study were heat transfer, power cycle thermodynamics, fluid flow and piping layout, and economic analysis.

The students concluded that such a district heating system was technically feasible, and designed a heating distribution system. They also concluded that such a distribution system and user conversion was very costly (ca. $45,500,000) and that outside funds were needed to finance the project. Two future design projects concerning financing and funding were spawned as a result of this original project.

Coors' upper management requested a final oral report in a company Technical Operations meeting. When the city fathers learned of the project, Golden's mayor requested that the students present a project report at a meeting of the City Council. The students, Coors, and the city management indicated that the project outcome was worthwhile.

STUDENT INTERACTION WITH DESIGN PROJECTS

THE DESIGN PROJECTS ARE paced by the groups. Aside from a few lectures on topics such as critical path diagrams, no formal lectures are given. Instead the professor acts as a resource person for informal interaction with the students. Each student is required to make a classroom oral presentation every second week on the progress to date. The engineering notebook, which includes all group work on the project and performance of tasks by each group member, is evaluated weekly by the professor.

During the second year of design in this mode, some of the positive reactions due to the innovative course nature were removed and the students were more objective. While some students complained about the inequality of the work load in each project, frequently students would suggest helpful ideas during other groups' oral presentations. The oral presentations not only allowed students to practice communication skills, but also gave the class exposure to the approach to each open ended problem.

Also, the students are able to use the personality typing skills in group solutions to the industrial problems. For example, a group with a majority of perceptive types was able to persuade the judgmental type to defer judgment and

obtain more data, while recognizing that they tended to defer decisions, sometimes longer than necessary.

EVALUATION

IN GENERAL, THE STUDENTS react very favorably to the course. They indicate that they are motivated because the problems are real and because the approach to the design process is applicable to the projects the students would encounter after graduation. The optimum atitude is typified by one student's comment; "I don't consider this work as course work anymore; it's something that I want to do." While some students feel that the time spent on group dynamics should have occurred after the design projects were assigned, all students felt that they had increased their self knowledge and their interpersonal relations during the personality typing portion of the course.

The industrial users all indicate a willingness to participate in the next iteration of the design course. They perceive the advantages of the course as 1) inexpensive engineering effort, 2) good corporate publicity and 3) an opportunity to evaluate potential employees. Within the limitations imposed by the effort, each company considers the group work comparable to that by new engineers working for them.

From the professor's standpoint, this type of design course has several benefits in addition to those previously mentioned. The students view the professor as a resource, not an adversary, to accomplishing the design project. The professor does not need to be the final expert on each design project, as he has the operating company as help with evaluation, guidance, and grading. The student's grades were based upon each company's judgments of the written and oral reports, peer evaluation by members of each student group, and evaluation based upon weekly oral reports and project notebooks.

The initial success of this course has aided in carrying out other iterations. The work done with the former companies was the basis for approaching other nearby companies for other real-world design projects. It is hoped that the benefits to the students as well as the benefits to industry will encourage wider interaction between academia and industry in the future.

ACKNOWLEDGMENTS

The author gratefully acknowledges support for the development of this course by a George R. Brown Innovative Teaching Grant. □

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REVIEW: LAB ENGINEERING

Continued from page 29.

laboratory problems. I found the book to be well written, topical and of practical use for the engineering type laboratory systems. The typical chemical research laboratory would greatly benefit if the ideas contained in the book were used in systems design.

Specific comments on each chapter are:

Chapter I: Well written, good illustrations, good descriptions, good compilation of usable data.

Chapter II: Easy to understand if one is mechanically oriented; could use a few more illustrations rather than only written descriptions. I believe there is almost too broad a subject matter covered in so few pages. Basic calculus used.

Chapter III: Good description of topic, good illustrations and practical. Would be useful to lab person with a grinding problem, etc. Some calculus used.

Chapter IV: One of the best written chapters in the book. Excellent descriptions and diagrams for the pumping of fluids. Very practical with good ideas for help in the laboratory.

Chapter V: The only thing this chapter needs to be 100% are a few more diagrams of the techniques. Excellent.

Chapter VI: An excellent summary of a very difficult theoretical subject, but written for the lay person. Very useful in any engineering laboratory

experiment or process system. Good illustrations.

Chapter VII: For the mechanical type laboratory oriented research person, this is a most practical chapter. Excellent descriptions and illustrations; most useful to anyone engaged in vacuum processing and systems design.

Chapter VIII: Good treatment of very complex subject matter. Simultaneous mass and heat transfer is not the easiest subject to learn or to adapt the theory to practical usage. This is the most difficult material for the non-engineer to understand unless the user has an excellent background in mathematics and good mechanical aptitude. Would suggest that whenever possible, more diagrams and sketches be added to simplify the material. Extensive calculus used.

Since all chapters are written by different authors, it is suggested that in the next edition a section be added that lists all of the nomenclature for all chapters.

In comparing the stated role of the book against the included techniques in the included chapters, it is found that in some instances there is little laboratory technique discussed. Also, the level of mathematical derivations is not consistent in the several chapters. □

PROCESS DESIGN SEQUENCE

Continued from page 37.

than they have seen before.

It is almost commonplace now to emphasize the importance of communications in professional advancement, and, at the risk of being trite, I must add my endorsement. Design courses usually require good report writing which students usually detest as an apparent over-emphasis on what they see as style as compared with substance. If anything is true, there must be more emphasis put on good writing and speaking. Facility in these areas is far more useful in practice than glibness with the computer.

Finally, one of the first skills a chemical engineer learns is how to do material and energy balances. These are also among the first steps in most design exercises. I feel strongly that these steps should be among the first in nearly any engineering assignment associated with processes. It may sound obvious, but it is too often forgotten how useful a simple balance can be in operations and research. Many of the steps taught in design sequences really do have other applications, and students should learn that fact.

In general, the chemical engineering taught in universities is more sophisticated than that practiced in many industries. Certainly, this is true for the food industry! Are students over-educated, as one might be tempted to say? I do not believe so.

Chemical engineering, culminating in the design sequence, is a grand education in analytical skills, modern science and technology. It is interesting enough to attract intelligent students and challenging enough to stimulate even the best. Furthermore, the influx of new concepts brought by products of this fine education will gradually change the industries they join. Far better that education continue to stress the new and sophisticated than the old and familiar—how else will we ever grow?

Having now been on both sides of the process design course "debate" (if there is such a thing!), I feel strongly that a varied, challenging and comprehensive course is essential to a complete chemical engineering education. I tried to provide such an experience when I taught and I look for the results in those I hire today. □

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SOLUTION OF DIFFERENTIAL EQUATION MODELS BY POLYNOMIAL APPROXIMATION

By John Villadsen and Michael L. Michelsen
Prentice-Hall International Series, 1978,
446 pages

Reviewed by D. Ramkrishna
Purdue University

This book is a welcome addition to the engineering literature. It introduces polynomial approximation for the solutions of differential equations with a demonstration of its performance in various problems leaning mostly on reaction engineering.

Chapter 1 lays down the scope of applications through a coverage of mathematical models commonly encountered in chemical engineering; more specifically, reaction engineering, separation processes, and polymer processing are some of the examples cited.

Chapter 2 contains an exposition of the *modus operandi* of polynomial approximation. The accent is on the approximation of the expansion coefficients while the choice of polynomials is essentially confined to those of the Jacobi class. Some useful computational schemes are introduced in Chapter 3 for efficient calculation of the polynomials.

Linear problems are the subject of Chapter 4 in which boundary and initial value problems have been treated. Nonlinear problems are dealt with in Chapter 5. The emphasis is on the nonisothermal catalyst problem (understandably so, since it has been actively investigated).

Chapter 6 is devoted entirely to a treatment of the one-point collocation method and its accomplishments (generally in reaction engineering) in spite of its startling simplicity.

In Chapter 7 demonstrations are made of the usefulness of the "global spline collocation" method in solving a variety of boundary value problems, especially entry length problems.

The discussion of coupled ordinary differential equations occupies Chapter 8. The treatment of stiff equations and parametric sensitivity of solutions deserves special mention.

The final chapter is concerned with the role of collocation (and spline collocation) methods in selected research problems. The low Peclet number Graetz problem, the asymptotic stability problem of a catalyst particle and fixed bed reactor dynamics are featured in this chapter. The Graetz problem at low Peclet numbers appears to have been treated well for the first time. In regard to this problem the criticism of Fourier series solution is somewhat inappropriate but excusable since it is based on past work, much of which has been plagued with errors. One also gets a good account of the catalyst stability problem for Lewis numbers different from unity.

The book makes comfortable reading for those with mathematical background normally available to graduate students in their first year of graduate school and qualifies for a supplementary text in a follow-up course on approximate methods; supplementary because of the constraint on *polynomial* approximations.

A feature that perhaps deserved some further attention in this book is the *convergence* of approximation methods. There are proofs available from functional analysis of the convergence of such methods to certain classes of operator equations. (The authors are not unaware of the role of functional analysis since they briefly allude to it in Chapter 5). While it would be a heavy undertaking to use the language of functional analysis in this book, it might have been possible to classify those equations for which convergence proofs are available along with rates of convergence). The restriction to differential equations becomes somewhat unnecessary especially because the use of approximate methods in other equations does not involve any special change of technique. Furthermore, while differential equations are indeed natural to chemical engineering models, integral equations of the Fredholm and Volterra types, and integro-differential equations (such as in population balances) occur with sufficient frequency to merit consideration. The omission of integral equations is not a special feature of this book but an unfortunate fact of the chemical engineering literature. Many realistic and important boundary value problems are best approached via integral equations.

Notwithstanding the foregoing criticism, this book is an important contribution to the chemical engineering profession because it brings together a class of approximation techniques that have been immensely valuable in the solution of a wide variety of engineering problems. □

ChE feature

CAREER PLANNING AND MOTIVATION THROUGH AN IMAGINARY COMPANY FORMAT*

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CAREER PLANNING HAS recently become a very popular topic for technical sessions at conferences [1], for workshops [2] and for books [3] [4] [5]. At the same time, we continue to have graduating students who are unaware of career opportunities and who do not appreciate how they can apply the fundamental knowledge to real problems. To provide some career planning and to motivate seniors by showing them how they will be using their knowledge to solve problems, we introduced the imaginary company format in a senior required course on process engineering. The objectives of the process engineering course have been described elsewhere [6]. In this paper we focus on the imaginary companies, the career planning components, the types of problems we use, and an evaluation.

Many have used an imaginary company approach for laboratories [7] [8] [9] and for design projects [9] [10].

What is unique about our effort is the use of career planning as a method for distributing the students among the companies and the extent and methods used by which we try to add realism to the company problems.

THE COMPANIES

WE HAVE ARBITRARILY selected the ten theme companies listed in Table 1. For each there is a job advertisement, an annual report, and a slide-tape show that provides an imaginary plant tour. At any one time only five companies are run simultaneously. Sufficient details are provided in each of these so that students see typical, real job advertisements for each industry, an annual report typical for the industry which describes the company produce line and, through the slide-tape show, photographs of typical processing equip-

TABLE 1
The Companies

THEME	IMAGINARY NAME	PRODUCTS
Petrochemicals	Petrostar	ethanol feedstock with acetaldehyde, acetic acid, acetic anhydride, acetone, vinyl acetates
Refinery Products	Big R	typical refinery
Polymers, Synthetic Fibers	Petropoly	PVC via suspension and emulsion polymerization, polystyrene, styrene, EDC
Foods	Fine and Fancy Foods	edible vegetable oils, lecithin, margarine, soy and peanut products
Inorganics	Inorganics Unlimited	chlorine, caustic soda, soda ash, cement, sulfuric acid, Claus sulfur plant
Pharmaceuticals	Canadian Drug	Aspirins, mycin, enzymes, baker's yeast, streptomyin, penicillin and bacitracin
Pulp and Paper	Spruce Mills	Kraft sulfite pulping, paper products and vanillin
Ceramic	Big C	Brick and tiles
Mineral Processing	Big Rock Mineral	Copper beneficiation, phosphate fertilizer, SO_2 abatement
Environmental	Enviroserv	Stretford process, impact of a sintering plant, flue gas desulfurization, amine scrubbing
Consulting	Technical Service Consultants	sulfuric acid production, tar processing . . . any current problem of interest

*Paper presented at the AIChE Free Forum on Undergraduate Education San Francisco, November 1979.

ment used by that industry.

Special letterhead paper has been prepared for each company; this must be used by the students for the covering letter that accompanies each assignment they hand in. Figure 1 shows a typical set of company information. Each company hires the course instructor to be its training officer. Thus, all correspondence and discussion with the students is between the instructor and them, with the imaginary third party (the company with its unique problems) providing realism for the problems. We elected to use the training-officer route because this is the day-to-day real life relationship between the instructor and the students.

THE CAREER PLANNING COMPONENTS

THE FIRST ELEMENT IN the career planning activities is self assessment [11]. We developed a 14-page self assessment instrument centered around Gaymer's book [5] and including ideas from Bolles [3] [4]. This instrument is sent to the students to be completed prior to entering the first term of their senior year. The assessment is personal; it is not shown to the instructor nor is it handed in to be marked. During the first week of term, the students spend about three hours in a tutorial run by the career counsellors during which time their answers to the self assessment are discussed and the implications described. Specially prepared materials are available [12] [13]. Topics discussed include how to extract from an experience the skills you developed, how to check for consistency in self assessment, what the unique skills imply as far as career development and plans are concerned, and how to integrate a set of separate skills into a career preference, plan and path. These counsellors are also available in the following weeks for private counselling. Our experience has been that more than two thirds of the students spend an additional hour in private guidance.

Once the unique skills and a career path have been identified, the students must be able to project their assessment through the "job" application (and eventually through the interview). Hints on how to apply and how to complete an application are given by all of us, although this is done primarily in a one-hour discussion led by Ron Romeo [14] [15].

The students are then given all the information about the ten companies: the advertisements, the annual reports, the slide-tape show and a "job"

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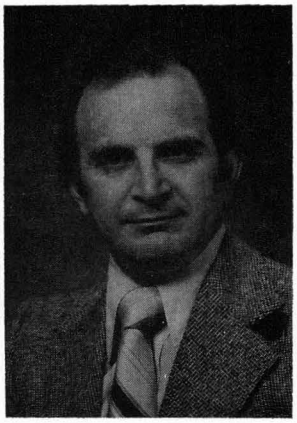
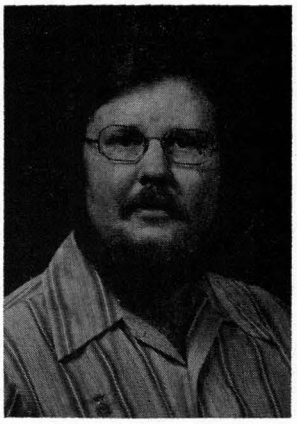
Carol Goodrow's previous experience in library science and university liaison is useful in her work as Career Counsellor with McMaster University students. She contributes to the development of career and job search programs and makes presentations to academic classes and professional associations. As Chairperson of the Career Information Resource Advisory Group, she is involved in evaluating and developing Canadian career publications. Ms. Goodrow received her Bachelor of Arts degree from Acadia University in 1967.





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David Lawson is a counsellor in the Student Counselling Service at McMaster University, Hamilton, Ontario. His particular area of interest is career planning and development. Prior to joining the counselling service in 1976, Mr. Lawson received a B.A. and Master's degree in Sociology from McMaster University.

Students are unanimous in their praise . . . and encourage us to introduce this earlier in the curriculum . . . The feedback from interviewers has been complimentary about the student's self awareness, ability to communicate skills, and mutual understanding of potential opportunities.

application form. They apply for one of the positions; their applications are evaluated and they are sent an appropriate letter of acceptance or rejection. Those rated "A" receive a bonus salary and those "B" or "C", a standard salary determined from a telephone poll of local industries. Those with late but acceptable applications are offered positions in isolated communities with no salary increase as compensation. Those with less than "C" are given rejection letters by their first choice company and must choose from among the other companies. To keep the work for the instructor reasonable, only five companies are run at a time. This is handled by running five each of two successive terms, with five companies accepting the applicant but delaying the appointment for one term. In the meantime, they choose one of those companies that is being run during the first term. The mechanics may sound complicated but it is actually simple to run. Standard letters have been prepared for each company so that annually we just fill in the student's name and salary.

In this way, students receive immediate feedback on both their self assessment and their ability to present themselves. As the term progresses, we hope that the students can assess, to some extent, their career choice through the types of problems they are asked to solve in that career path.

TYPES OF PROBLEMS

The problems are chosen from the context of the course on process engineering which considers the analysis of the structure of chemical processes, an analysis of the function of process equipment in different processing contexts, equipment design and selection, safety, time and project management, ethical and legal considerations, financial aspects of a corporation, engineering economics, financial attractiveness criteria, capital and operating cost estimation, economic balances, optimization, developing rules of thumb, and case studies to illustrate the application of these ideas in process operation, improvement, design and research and development. These include the use of trouble shooting problems and the development of problem solving and decision making skills [6] [16] [17] [18]. This context provides a rich environment in which to cast the imaginary company problems. The problems can be created or used directly from a text but cast into the context of the company. Small problems from local industry or from consulting are used for some of the problems. Some illustrative example problems are given in Table 2 (Details are available from Donald R. Woods).

EVALUATION

STUDENTS ARE UNANIMOUS in their praise of the career planning components. Indeed, they encourage us to introduce this earlier in the curriculum instead of in its present location as the first semester of the senior year. The feedback from company interviewers has been extremely complimentary about the student's self awareness, the ability to communicate their skills, and the mutual understanding of each other's potential opportunities.

The actual week-by-week operation of the companies presents an initial faculty load in preparation of the context. It also provides further incentive to bring new practical problems into the course; problems from a variety of industries that one normally does not follow up. For example, we are currently trying to improve the problems which illustrate applications in the ceramics and mineral processing industry. Most companies are very helpful.

The student's response to the problems has been mixed, partly because we are still developing

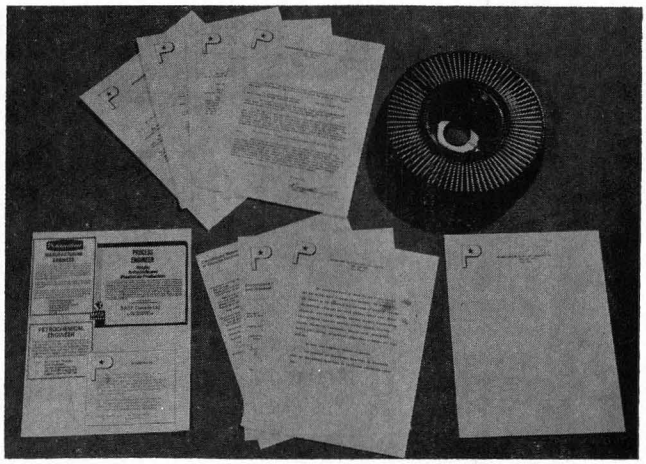

FIGURE 1. Information pertinent to the imaginary company.

TABLE 2
Typical correspondence—assignments

1. Letter of Offer	
2. Analysis of Financial Report (participation in stock option)	Related to Ch. 3 of Text
3. Flowsheet development for the products	From the literature
4. Analysis of Structure of a Section of the Process	Application of ideas from class
5. Financial Attractiveness Criteria	Problems from Text in company context
6. Capital Cost Correlations	How to use different correlations
7. Plant Capital Cost	Integrating the data into complete plant costs
8. Production Cost Estimation	
9. Safety analysis	
10. Trouble Shooting Problems	

the problems and smoothing out the mechanical details. Nevertheless, the students enjoy seeing what types of problems characterize different career opportunities and how the same fundamental ideas can be applied in a wide variety of contexts.

SUMMARY

TO HELP STUDENTS DEVELOP career plans and to motivate senior students, we provide opportunities for self assessment into an application for one of ten imaginary companies. Basic information is given for each company. During the term the students solve problems written in the context of the company for which they are working.

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CRITIQUE OF DESIGN COURSE

Continued from page 33.

On the other hand, should chemical engineers boldly strike out and endeavor to develop new forms for "the creative application of fundamentals to practical problems?" Or would another kind of course provide a better synthesis experience for our times? Do we see a candidate in a course based on the text "The Structure of the Chemical Process Industries," by Wei, *et al.* [13]? As stated in its preface, this book has the worthy purpose of making one understand "how chemical technology is mobilized to benefit society, and how chemical engineers can contribute effectively to it."

The design course may be in a rut. If so, changes for just the sake of change (a common motivation for curriculum redesign) should be avoided unless the contending schemes are superior to traditional programs. New directions are encouraged by the 1979 definition of the design experience in education [12] The book by Wei, Russell, and Swartzlander suggests a new kind of capstone experience. □

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APPENDIX

For running in still air at velocity v, the drag force of the wind is:

$$F_{wind} = C_d \rho_a v^2 A \tag{1}$$

Assuming a cylindrical form of radius r and height H for the body, the projected area is:

$$A = 2rH \tag{2}$$

and the volume is:

$$V = \pi r^2 H = \frac{M}{\rho_b} \tag{3}$$

Elimination of r in Eqn. (2) using Eqn. (3) gives:

$$A = \frac{2}{\sqrt{\pi}} \sqrt{\frac{MH}{\rho_b}} \tag{4}$$

The mechanical power for overcoming wind resistance is:

$$P_{wind} = F_{wind} \cdot v \tag{5}$$

Substituting Eqns. (1) and (4) in (5):

$$P_{mech} = \frac{2}{\sqrt{\pi}} C_d \rho_a v^3 \sqrt{\frac{MH}{\rho_b}} \tag{6}$$

The error resulting from the incorrect assumption of cylindrical form is cancelled by calculating C_d from experimental data [5] for the drag force on the body during running. Defining $\rho_b = 1000$ kg/m^3, the drag coefficient C_d is found to be 0.50.

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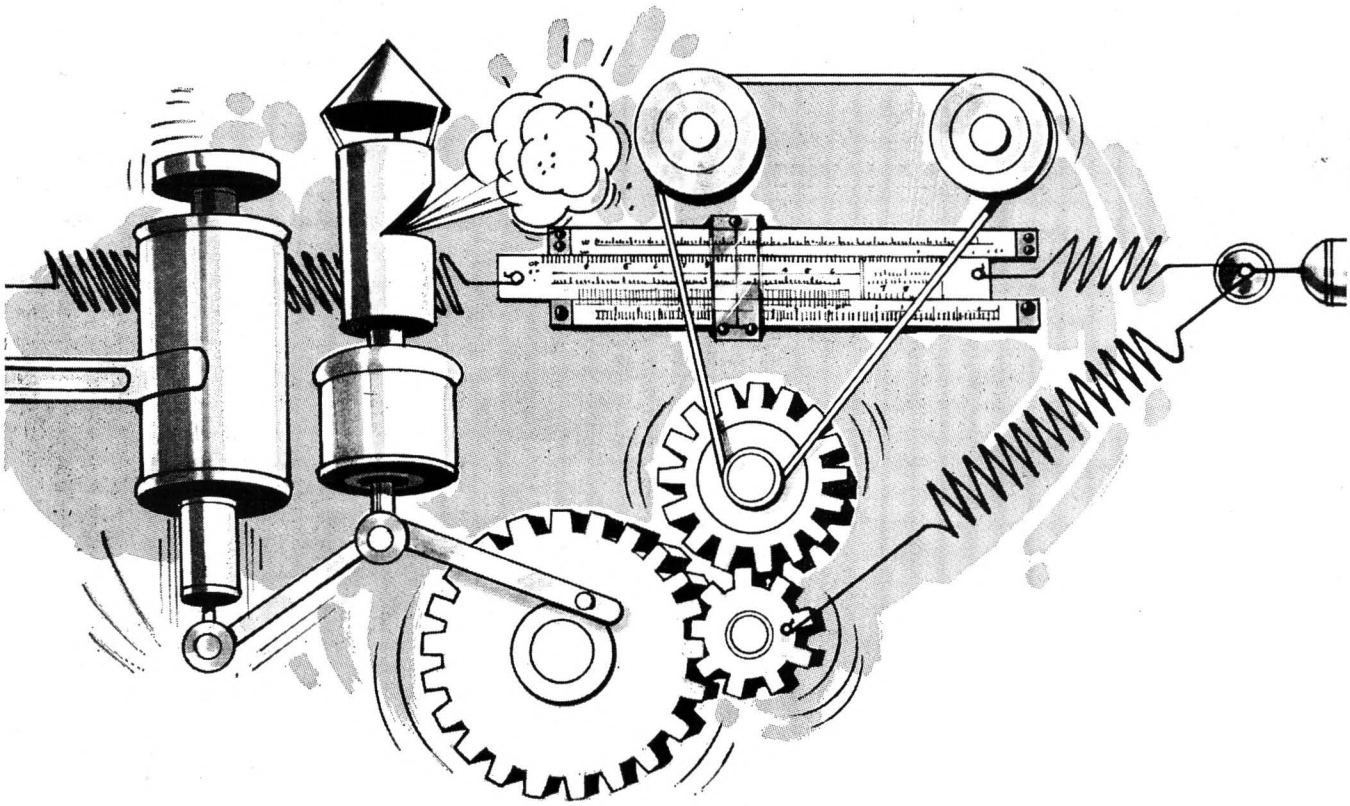

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