

CEE

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SUMMER 1974

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION



ChE Educator
TURK STORVICK
of U. of Missouri-Columbia

ChE at OHIO STATE

DESIGN ISSUE

ODEN

Teaching Plant Design

LASHMET & SORENSEN

Cost Estimating By Computer

CADMAN

Computerized Cost Engineering

MARTIN

Expansion and Contraction Losses

REILLY, TIMM & EAKMAN

Nebraska's Integrated Process Lab

GADDY

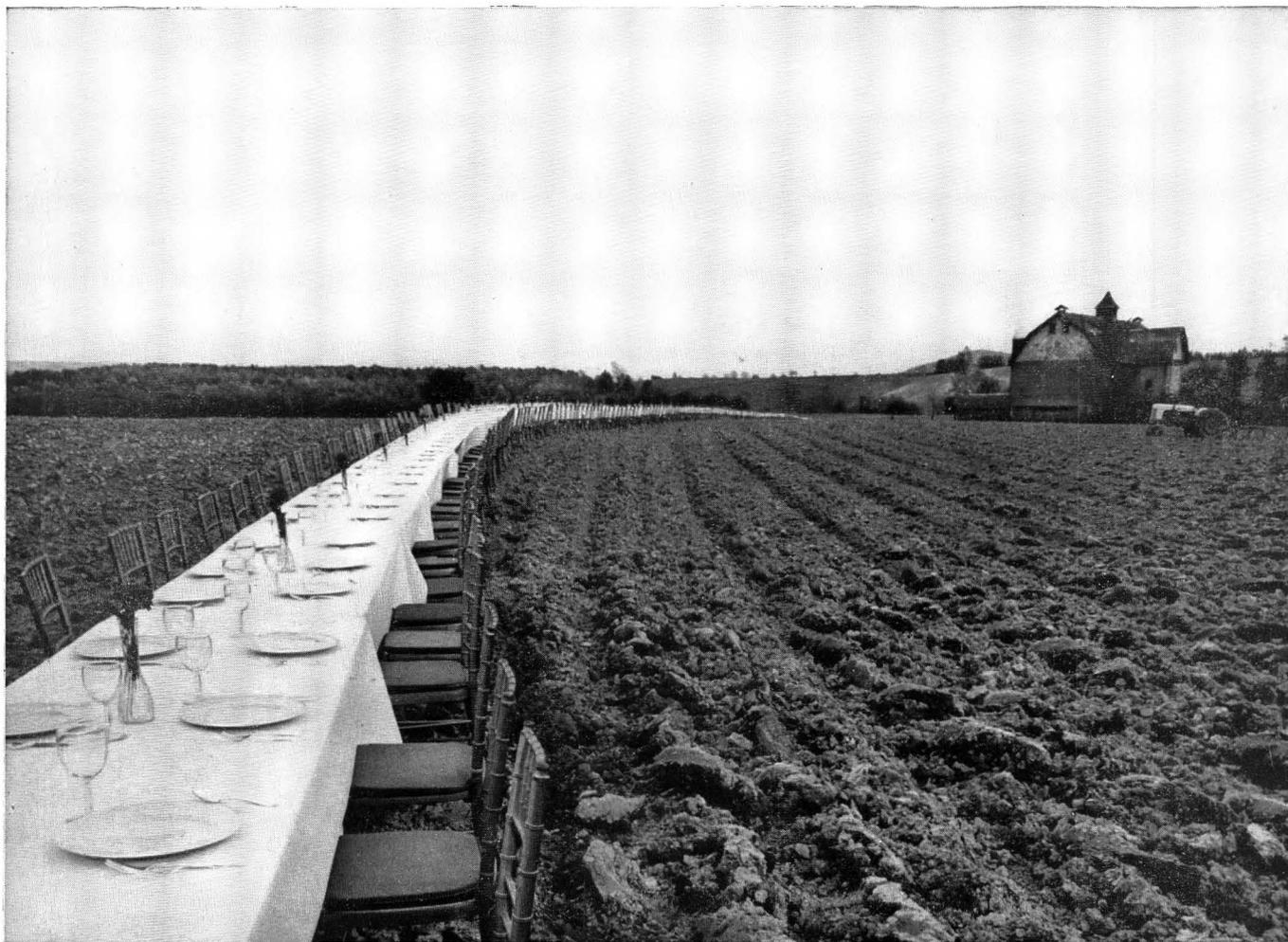
Using Flowsheet Simulation Programs

ALSO:

SEEING ENTROPY: Sussman

CO-OP EDUCATION: Tucker

We're expecting a few extra people for dinner tonight.



Tonight, the world will have 213,000 more mouths to feed than it had last night.

Unfortunately, we're not growing food as fast as people.

But there's still hope of reversing the trend.

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only save food crops from bugs, but destroy themselves afterwards.

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Because those 213,000 guests are coming — whether we're ready or not.



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will touch your life.**

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OHIO STATE



ChE FACULTY
Ohio State University
Columbus, Ohio 43210

IN 1974, THE DEPARTMENT of Chemical Engineering at The Ohio State University will grant its 3000th degree. The lucky lad or lass who receives it will be joining the graduates of one of the most senior engineering departments in the nation. Three-quarters of a century have passed since the university granted its first "bachelor of science in chemistry for the Engineering College."

Headquartered in a four-story glass and brick building located in the midst of The Ohio State University engineering-physical science complex, the Chemical Engineering Department today has 13 faculty members, is the occasional home for visiting professors and post-doctoral students, grants degrees at the bachelors, masters, and doctoral level, and is the site of a diversified research program.

Ohio State's Chemical Engineering Department has one of the best-equipped "Unit Operations" laboratories available today. The modern four-story laboratory provides basic "hands-on" training for every student of chemical engineering. It is equipped for work in distillation, absorption, evaporation, drying, extraction, filtration and sedimentation. The equipment is arranged in such a way that a variety of experimental projects can be carried out by operating each unit individually or as part of an integrated process. The lab has a central control room and much of the equipment is being adapted for computer control.

The building contains a number of special laboratories such as a physical-measurements laboratory; micro-plant process development laboratory; and a Class 1, Group D, high-ventilation laboratory for polymerization and drag-reduction research. The department facilities include a nuclear laboratory; reservoir engineering laboratory; combustion research laboratory;

rheological laboratory and an analytical laboratory equipped with gas chromatographs, ultra-violet and infra-red spectrophotometers, and a mass spectrometer.

In addition to these special laboratories, there are 13 research laboratories equipped for two to four students. A number of special pieces of research equipment are in use, such as PVT apparatus, rheogoniometer, mass transfer apparatus for flow in micro-porous solids, recycle catalytic reactor system, and absorption apparatus.

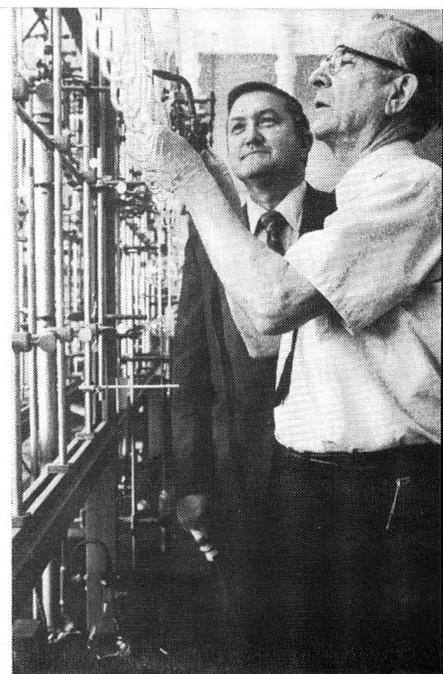
DUAL COMPUTER SYSTEM

A VAILABLE FOR TEACHING and student research is a PDP-15 dual computer system that is unique in that it is a combination of two computers working together as a dual processor. The computer with its accessories is versatile and fast because of this configuration. It has four principal uses in the chemical engineering department: data acquisition and analysis; process dynamics and control; simulation and optimization; and support of classroom and laboratory instruction. Considerable analog computer equipment is also available and can be run in conjunction with the digital facilities.

The PDP-15 has a variety of input and output devices. Inputs to the computer can come from the Unit Operations Laboratory and simultaneously from any of several other labs throughout the building. The computer may be used for



Karl Svanks, Ed Haering and Al Syverson scan the results of an adsorption-reaction experiment in the catalyst laboratory.



'Slip' Slider watches as Web Kay prepares for PVT measurement.

control for which output voltage signals may be sent to experimental units at various locations. Data, computations, and programs can be stored on paper or magnetic tape. While a line printer is available, remote teletypes and video displays are often used for the output of experimental data. In the main computer room there are three types of video outputs.

The polymer research and rheology facilities allow a complete range of experimentation. Equipment in this area includes a 2½" NRM — 24/1 plasticating extruder equipped with a sheet line, beta gauge thickness measuring unit and all that is needed for real-time on-line data acquisition. Also in the polymer research area is a complete Waters Assoc. Model 200 Gel permeation chromatograph with dual pumping system and a Weissenberg rheogoniometer equipped for on-line real-time computer data acquisition.

The department has a well-equipped laboratory for the determination of the PVT properties of liquids and gases covering a range in pressure and temperature from ambient conditions to 125 atm and 350° C. An array of special equipment is used for precision measurements and to insure purity of all chemical components. Vapor pressure, saturated liquid- and vapor-densities from low temperatures and pressures to the critical point, compressibility of gases and vapor/liquid equilibrium compositions in mixtures both at low and high pressures can be determined.

Extensive equipment exists for studies in drag reduction and on the basic fundamentals of turbulent flow. Of major importance is the visual

The department has a long tradition of close relationships with students, alumni and industry. . . We recognize that for most practicing engineers, the undergraduate experience serves largely as a catalyst for a lifetime of learning.

study loop which consists of a test section and system for transport of the high-speed camera and light source. Temperature control is within 0.1° C. A boundary-layer facility is available that utilizes the same camera transport system. Other turbulence measuring equipment is available.

The main reason that this great array of equipment has been assembled is for enhancing the educational opportunities for our students. The student is the center of focus for all programs; the existence of any facet of our educational endeavors depends upon the benefits he receives.

The department has a long tradition of close relationships with students, alumni and industry which have had a substantial influence on the educational philosophy and goals of the department. We recognize that for most practicing engineers the undergraduate experience serves largely as a catalyst for a lifetime of learning. The effectiveness, versatility and adaptability of the chemical engineer, so important in the past and so promising for the future, arises from a broad base of fundamentals in his training coupled with the ability and motivation to put these to practice. Thus, the general aims of the undergraduate programs are to provide the students with a broad and intensive background in fundamentals of science and engineering and practice in applying these to the creative solutions of real problems. Approximately 45 students complete the baccalaureate requirements each year.

UNDERGRADUATE CURRICULUM

THE UNDERGRADUATE curriculum begins with courses in physics, mathematics, and chemistry. Studies in chemical engineering begin in the sophomore year with courses in material and energy-balances and an introduction to transport processes. During their junior year, students

continue studies of the fundamentals in courses dealing with transport phenomena, thermodynamics, chemical engineering operations and process control and analysis. This classroom work is illustrated and applied in several laboratory courses.

During the senior year, a semi-integrated sequence of courses deals with reaction kinetics, economics, and process development, followed by a rigorous process design course. The final project of the senior year is the synthesis, analysis, simulation, and optimization of a commercial scale process encompassing most of the undergraduate work.

An important aspect of the senior year is the opportunity for the student to gain depth, as well as breadth, in an area or areas of his interest through a Technical Option or Elective Program. Available to chemical engineering students are 18 credit hours for programs in bio-engineering and



Chris Geankoplis and Ed Smith are shown the sample probe for the particulate collection apparatus by Tom Sweeney.

biochemistry, environmental engineering, advanced mathematics, petroleum-reservoir engineering, polymer engineering, nuclear engineering and process dynamics and control. Many of these courses may be taken outside of the department. Additionally, there is a pre-medical option that prepares the student for entrance to medical school. A rearrangement of elective courses in biology and zoology allows the student to take the medical school examination during the Spring quarter of the junior year.

A large university, of which Ohio State is perhaps a typical example, can provide unusual educational opportunities. The University offers in-

struction in 150 subject areas through 114 academic departments and 7800 individual courses. Outstanding university-wide supportive facilities such as libraries, computers and interdisciplinary centers and programs are available. Two elective programs are required in order to expose the student to areas not in the skeleton curriculum. Thirty quarter hours must be taken in the social sciences and humanities. An additional twelve hours of "free" electives are required. Each student is encouraged to select, with the assistance of a departmental faculty adviser, a coherent sequence of courses that explores in depth an idea or theme of special interest to her or him.

GRADUATE PROGRAMS

AT THE POST-BACCALAUREATE level, 45 to 55 full-time students are enrolled in any year. In an average year, 18 students receive a masters degree while from six to seven students complete their doctoral program.

Requirements for the master of science degree include 36 quarter hours of course work and a research thesis for a total of 45 quarter hours. The course requirements include completion of a series of courses in transport processes, thermodynamics, reaction kinetics and mathematics. The remainder of the course program is planned with the assistance of an adviser to meet the needs and desires of the student. A wide variety of courses is available both within and outside the Department. A final oral examination on the thesis completes the requirements. Most students with adequate undergraduate preparation obtain the degree in one calendar year.

The doctoral program provides the student with the opportunity to carry out independent study under the general supervision of his adviser. The aim of the program is to provide meaning to research as well as a greater depth of understanding of chemical engineering. The program requires 135 quarter hours beyond the bachelor degree of which three quarters must be in residence. Students may continue with the Master's degree adviser or through a student/faculty-interaction process may select another adviser. The student with assistance and guidance of his adviser will plan a program of 75 quarter hours of course work (including those required for the Master's degree). A core of advanced courses in chemical engineering and mathematics



Emy Lynn and Bob Brodkey inspect the last few meters of the more than 15 kilometers of sheet recently produced with the extruder.

is required. The balance of the course requirements is chosen from other chemical engineering courses supplemented by a minor outside the department.

The doctoral language requirement is the satisfactory completion of two college-level courses (or the equivalent) in a single foreign language. Written and oral General Examinations are taken upon the completion of the course requirements. Research culminating in a satisfactory dissertation and an oral defense of the research complete the requirements.

FACULTY RESEARCH ACTIVITIES

THE RESEARCH INTERESTS of the 13 faculty members of the department range over most areas of chemical engineering. The balance between staff and graduate students allows close personal contact, an essential ingredient for effective teaching in research. Students are expected to explore research opportunities with a number of faculty members before selecting a specific area.

An important aspect of the senior year is the opportunity for the student to gain depth as well as breadth in an area of his interest through a Technical Option or elective program.

Fundamental research in fluid mechanics by Professors Robert Brodkey and Harry Hershey involves visual and anemometry studies of normal and drag reducing fluids in turbulent shear flows. Such studies are designed to elucidate the mechanism of these quasi-random processes.

Studies in bioengineering are diverse. They include the phenomena of blood clotting in the presence of plastic replacement parts being studied by Professor Brodkey and diffusion of proteins in blood by Professor Christie Geankoplis. Professors Brodkey and John Heibel are studying computer applications such as speech pattern recognition and x-ray data gathering in hospitals. Professors Ed Smith and Geankoplis are doing research in diffusion of enzymes and proteins in milk and gels and fermentation and growth rates of microorganisms in biological processes. Professor Aldrich Syverson is studying the kinetic factors related to catalyst and reactor design using immobilized enzymes in food plant waste utilization or treatment.

Professor Tom Sweeney is involved in research in air pollution-control techniques and devices, small-particle technology, and process modification. Professors Smith and Karl Svanks are studying the concentration, distribution, and analysis of nutrients in Lake Erie water and problems in acid mine drainage treatment.

Professor H. C. Slider is studying methods of maximizing the producing rate and ultimate recovery from subsurface gas and oil reservoirs by doing research in miscible displacement fundamentals and single well secondary recovery. Professors Smith and Svanks are studying methods of processing high molecular weight petroleum oils and methods for analysis of solid fuels such as coal.

An integrated approach to the varied problems in polymer engineering research is being conducted in the department. Professor Emerson

Available to ChE students are 18 credit hours for programs in bio-engineering, biochemistry, environmental engineering, advanced mathematics, petroleum-reservoir, polymer and nuclear engineering, and process dynamics and control.



Ed Freeh, Harry Hershey and John Heibel go over a recent change in the PDP-15 operating manual.

Lynn is doing research on polymerization and polymer recovery. The basic extrusion mechanism is being investigated visually by Professors Brodkey and Lynn and the extruder system is being modeled on a real-time digital computer by Professors Ed Freeh, Lynn, and Heibel. Research on the rheology of polymers using a kinetic theory approach for viscoelastic systems is being done by Professor Brodkey.

The role of mechanisms of reactions, high-speed adsorption at reaction conditions and transport of adsorbable gases in gaining a better insight into the physico-chemical phenomena in heterogeneous catalysis is being studied by Professors Syverson and Ed Haering. Professor Brodkey is doing research on the interplay between turbulence, mixing and kinetics. Reactor design scale-up, and modeling research is being conducted by Professors Haering and Freeh. Research on the thermodynamic properties and phase behavior of polar and non-polar mixtures is being done by Emeritus Professor Webster Kay and Professor Hershey.

Studies in the Knudsen and transition diffusion of gases in capillaries and porous solids as well as diffusion and chemical reaction in liquids are being conducted by Professor Geankoplis. Professor Sweeney is doing experimental and computational studies of the contact resistance to heat transfer at the interface between two solids. Basic chemical engineering concepts are being used by Professor Smith in research in combustibility of materials and the modeling of fires in buildings. Professor Haering is doing

work toward providing better chemical engineering techniques for industrial process design.

The department's real-time, time-share digital computer is under the direction of Professors Freeh and Heibel. Application of this facility is being made to many of the problems cited elsewhere and is extensively used as an on-line data acquisition system and for process control. Professors Brodkey and Hershey are working in modeling of heat and mass transfer in turbulent flows as well as various optimization procedures for model evaluation. Professor Slider is modeling three-dimensional, multiple-phase displacements in petroleum reservoirs in studying oil displacement efficiency.

EVOLUTIONARY PROCESS

The purpose of this paper has been to describe the department as it is today. Since the present has evolved from many rich traditions of the past, a very brief history of the department seems appropriate.

Chemical Engineering at The Ohio State University evolved from an industrial chemistry program which began about the turn of the century. Chemical Engineering was a division of the chemistry department from 1902 to 1924 when it

During the past 70 years, the department has granted 1850 B.S. degrees, 857 M.S. degrees and 267 Ph.D. degrees.

was granted the status of a department in the College of Engineering. (To those who are dealing with budgets today it might be of interest to note that the total budget for the department for 1925 including salaries, supplies and equipment was \$13,837.59.)

A five-year program for the Bachelors degree along with an honors or "combined" program for the M.S. degree was established in 1945 and continued until 1969 when the present four-year program was adopted. Dr. James R. Withrow directed the program from 1906 to 1923 when chemical engineering was a division in Chemistry and served as the first Chairman of the Department of Chemical Engineering from 1924 to 1948. Dr. Joseph H. Koffolt was Chairman from

1948 to 1968, followed by Dr. Aldrich Syverson, the present Chairman.

During the past seventy years, the Department has granted 1850 Bachelors degrees, 857 Master of Science degrees, and 267 Doctor of Philosophy degrees. There are at the present time approximately 2250 active alumni employed by more than 500 industrial firms, government agencies or academic institutions throughout the United States and in more than forty foreign countries. Seventy-one alumni are teaching in 50 colleges or universities in this country; twenty-five are teaching in 16 foreign countries. □

SUMMARY OF UNDERGRADUATE PROGRAM

	Quarter Hours
MATHEMATICS and SCIENCES	
Mathematics	28
Chemistry	39
Physics	15
	—
	82
CHEMICAL ENGINEERING	
Mass and Energy Balances	6
Transport Processes	9
Thermodynamics	6
Chemical Engineering Operations*	11
Kinetics	3
Process Analysis and Control*	4
Economics	3
Process Development*	4
Process Design	5
Inspection Trip	2
Senior Seminar	1
Technical Electives	18
	—
	72
*Includes laboratory	
OTHER	
Engineering Mechanics	5
Engineering Graphics	5
Introduction to Computers	3
Engineering Survey	1
English (includes technical report writing)	8
Basic Education (Humanities and Social Sciences)	30
Free Electives	12
Physical Education	2
	—
	66
Total	220

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Turk Storvick

of University of Missouri-Columbia

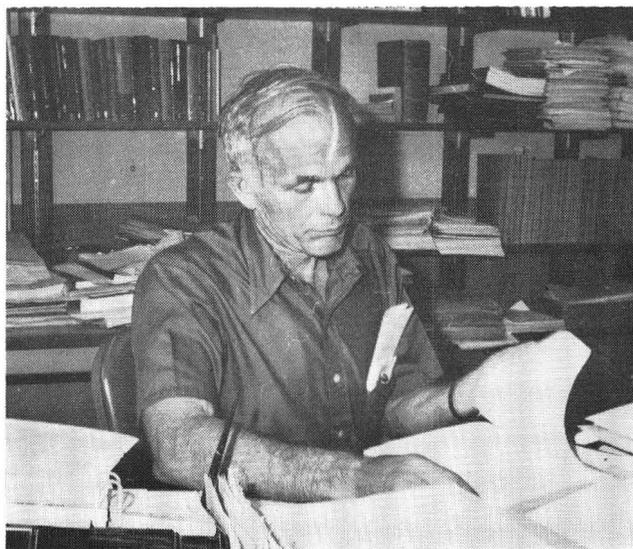
THE ChE FACULTY
*University of Missouri
Columbia, Missouri 65201*

IN 1946, IT WAS customary for the citizens of Albert Lea, Minnesota, to draft their men as eighteen-year-olds for Army service, whether or not they had finished high school. Truman S. Storvick started his professional career by enlisting in the Navy because as a naval enlistee for a two-year hitch, he was allowed to finish his senior year and consequently had the opportunity to hear the commencement speaker, the young mayor of Minneapolis, Hubert H. Humphrey.

After being shaped up in boot camp in San Diego Storvick was "drafted" to play center on one of the football teams at the Naval Air Station in Jacksonville, Florida. Running under a kick-off on the specialty team, he suffered a knee injury which put him in the station hospital for eight months and ended the start of a brilliant naval service football career.

The thoroughness and precision of H. C. Van Ness' presentations in thermodynamics and the wide range of interests and the boundless energy of J. M. Smith provided additional marks.

The Navy, which does not give up very easily, assigned Seaman Storvick to the aviation division on the light cruiser U.S.S. Portsmouth, which was the flagship for Admiral Sherman, commander of naval operations, Mediterranean area. Here he learned the old and revered saltwater art of hollystoning of teakwood decks, and that the energy stored in a half-mile of $1\frac{1}{2}$ " diameter tow cable, oscillating to the breaking point between two



Meet the Turk.

warships, is huge indeed. His travels with his naval colleagues carried him to Gibraltar, Italy, Sicily, Greece, Malta and Algeria, which were in a generally impoverished and damaged condition as a result of World War II action.

THE NAVAL SERVICE was not an end in itself; so armed with a naval discharge Storvick took up an academic career in chemistry at St. Olaf College in Northfield, Minnesota. With the knee injury preventing him from picking up a football career, he became the team's trainer and manager. With energy to spare, he and another freshman, Dick Ovington, organized St. Olaf's first wrestling team, and persuaded Professor Hauberg to be the coach. Storvick's opponents in the 165-pound class learned what it meant to be wrestling with a "Turk." Spring brought the track season and more diversion from study.

Chemistry and athletics hardly filled the week, so there was time to meet Lynn Abrahamson, who later became Mrs. Storvick, who was one of his fans. Another year showed that a career in chemistry did not interest him as much as

he originally thought, so it was off to Iowa State University where chemical engineering was a full-time major.

Chemical engineering at Iowa State provided the inspirational teaching of Gerry Beyer and a very short but enriching experience with Morton Smutz. Unit operations under B. F. Ruth with those 105 heat transfer and fluid flow problems in one quarter (at slide rule speed) made a lasting impression. Academic work was put in perspective with part-time work in the Engineering Experiment Station in the oil seed solvent extraction laboratory directed by Doc Arnold and the tutelage of graduate students Dennis Griffin and Bill Juhl.

INDUSTRIAL WORLD

WITH A B.S. DEGREE, Turk and Lynn set out into the real world. His supervisor with Westvaco Division of FMC in South Charleston, West Virginia, was George Sklar who had him unraveling difficulties in a packed distillation tower for the separation of by-products from ethylene dibromide before he was assigned an office. This led to other challenging work in the pilot plant, field construction inspection, operation manual preparation, operator training and plant startup for Westvaco's methane-sulfur to carbon bisulfide plant. Some preliminary cost analysis filled some weeks before "we scaled up Gilman's Organic Synthesis procedure for making unsymmetrical dimethylhydrazine (or how do you swirl a 1000-gallon Florence Flask)". This led to the initial development studies on the catalytic hydrogenation process for making UDMH as the space program demands increased.



"Running—the best sleeping pill I've ever found."

After boot camp, Storvick was "drafted to play center on one of the football teams at a Naval Air Station."

RETURN TO ACADEMIA

THESE EXPERIENCES convinced Turk that there was a good deal about chemical engineering that should be learned if he was going to continue his work in engineering research; so off he went to Purdue. *The thoroughness and precision of H. C. Van Ness' presentations in thermodynamics and the wide range of interests and the boundless energy of J. M. Smith provided additional marks. Alden Emery only claims to have "signed the forms" for the peripatetic Joe Smith who served as dissertation supervisor, but his style was also an important factor in the Purdue venture.*

A semester as an instructor whetted Turk's interest in teaching and an invitation from Gerry Beyer to visit the University of Missouri followed. A trip on the Wabash Cannonball from Lafayette to St. Louis, the Wabash Railroad to Centralia, Missouri, and the final twenty miles to Columbia on the Wabash spur provided the introduction, and he joined the faculty of Old Mizzou in February, 1959.

The calorimetry work with Joe Smith revealed some deficiencies in the p-v-T data and transport properties of gases. With lots of help from the National Science Foundation (NSF), facilities were built to make p-v-T and viscosity measurements on gases at high temperatures and pressures to provide tests for available theoretical models of these properties. Later, a study of the thermal conductivity of gases led to building an apparatus to measure the thermal transpiration effect in gases and a hard look at gases at low pressure.

Turk has a reputation for being where the action is. When digital computers were introduced to assist students in the solution of their assigned class problems (and by the way, engineers working in industry were also encountering their use), he worked to support this academic function by engaging in a number of academic "administrative skirmishes." It's always essential to maintain a sense of humor in these activities and after decisively losing one such battle, he pre-

sented the graduate a bottle of bourbon ("I found out later he drank only Scotch") and a congratulatory speech. The irresistible move toward massive centralized computing systems proceeded as Turk and Sam Dwyer ("the hardest working guy it's ever been my pleasure to know")

With energy to spare,
he and another freshman organized
St. Olaf's first wrestling team.

spoke for the development of engineering laboratories based on small, special purpose computers for research and teaching. "The pocket-sized desk calculator and small, special purpose computers have revolutionized engineering education, research, and practice for the fourth time in twenty years. The next change will be miniaturization and reduced costs with yet another big change before 1980."

Classical chemical engineering education provided poor tools to read the chemical physics literature, so armed with a NSF science faculty fellowship, he spent a sabbatical year at the University of Maryland's Institute for Molecular Physics in 1965-66. Private readings in statistical mechanics and kinetic theory were supplemented by attending formal courses taught by J. Robert Dorfman and Elliot Montroll. Five papers were published jointly with E. A. Mason and Andrew DeRocco on the IMP staff and Tom Spurling, a postdoc from Australia, all of whom provided the excellent environment for work there. The IMP seminar series broadened the horizons as the outstanding chemical physicists living on the east coast came through and discussed their work.

The Thermodynamics and Transport Properties Research Center was set up and directed by Turk under a DOD Project Themis grant in 1967. L. B. Thomas and Bob Harris from chemistry, Paul Schmidt from physics, Dick Warder from mechanical engineering and Jack Winnick from chemical engineering provided the supervision and six post doctoral and some thirty pre-doctoral students contributed to a wide range of work that produced about forty papers over the five-year period of support. "This program provided one of the Federal Government's finest expressions of support for academic research and graduate education."

His classrooms at both the undergraduate and graduate levels are informal learning arenas. Students rate him highly as an instructor and look forward to getting into his classes. The "secret, if there is any that works, is to bring the student into an encounter with the course

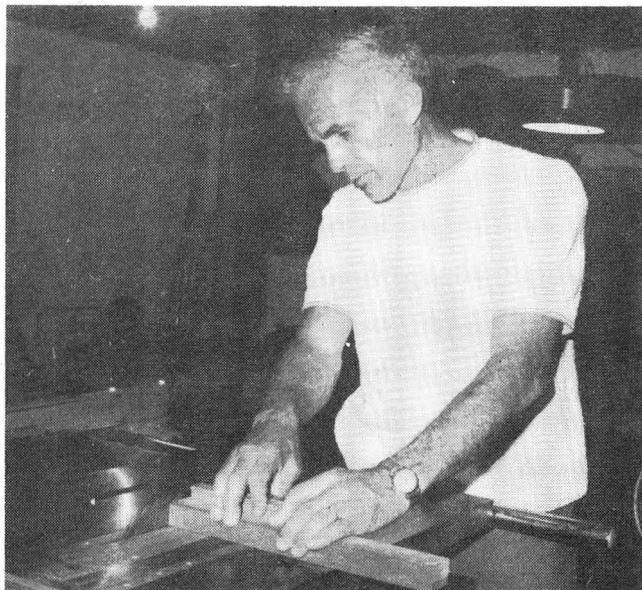
material rather than with the instructor. To the degree you can do this for each person in the class, you can be successful." He is never too busy to assist a student in difficulty whether he is in the classroom, the laboratory or on the campus.

Proceeding from the view that a "sabbatical leave is one fringe benefit which makes the unsavory parts of academic life bearable," as the Robert Lee Tatum Professor of Engineering, he was awarded a senior postdoctoral fellowship from the Royal Norwegian Council for Scientific and Industrial Research at the Technical University in Trondheim, Norway. This provided time for individual detailed study of the kinetic theory of gases near solid boundaries. "We have no general theory that describes the behavior of gases in the transition flow regime. Our work on thermal transpiration requires this theory and it is essential that we work on this problem. S. K. Loyalka of the UMC Nuclear Engineering Department has made significant contributions in this field and the opportunity to work with him should be most interesting and fruitful as we learn more about the slip phenomena and perform the necessary experiments this work suggests." The hospitality of Professor Aksel Lydersen and the staff in the Institutt for Kjemiteknikk made this a once-in-a-lifetime experience for him in 1972-73.

ACTIVE RELAXATION

OUR YEAR IN NORWAY was really family-centered." The Storvick children, Jan, Kris and Ole attended Norwegian schools (Ruth was a college freshman in the U.S.), and learned Norwegian, which they use currently. Cross country skiing is a national competitive sport, but on a winter week-end, everyone from crib to ninety headed for the ski trails that cross the forests covering the mountains. "The crystal beauty after a snowfall is just spectacular, and each turn in the trail is a picture-scene." The winter ski trails the Storvicks traversed became their summer

Students rate him highly as an instructor and look forward to getting into his classes . . . he is never too busy to assist a student in difficulty whether he is in the classroom, the laboratory or on campus.



Wood responds to careful work and attention.

hiking trails as the long winter nights were transformed into the perpetual light of midsummer night. A trip to the ancestral farm near Sundal-øra and a visit with the Storvicks who now live in Kristiansund provided a connection to the past. "Traditional celebrations in Norway were familiar since they survived the transplantation to Minnesota, and the passage of time, and were carried out by my parents."

Relaxation means working with the hands. Storvick's well-equipped home workshop transforms rough-sawed, seasoned walnut into custom designed furniture. "Wood responds to careful work and attention. The hidden beauty of the grain and color become a part of the design of the piece." Needlework, learned in Norway, has been added to his activities ("If Rosy Grier can do needlepoint, you can't call it lady's work in the Ms. age."). Turk has served as an elder in the Presbyterian Church, sung in church choirs and recently with the Musicum Collegium group at UMC, which performs vocal music from church and court dating from the fifteenth to the seventeenth century.

Contrary to popular belief, the departmental faculty at UMC are not recruited for their distance running abilities. Turk, a faculty member long before the F. J. Van Antwerpen Trophy for Physical Achievement was instituted, has twice been a member of the winning four-mile relay team. This past year he ran a record time of 5:24.1 for his leg of the relay and along with Dick Angus, Marc de Chazal and Dick Luecke, won the trophy for the third consecutive year. Running and handball provide outlets for frustrations and "the best sleeping pill I've ever found."

The Ph.D. program was initiated at Old Mizzou in 1944, but the number of graduates began to increase after Turk's arrival. The work load certainly was shared by those already aboard (Marc de Chazal and Gerry Beyer) and by other recruited members. Jack Winnick (Oklahoma), Dick Angus (Princeton), Dick Luecke (Oklahoma), V. J. "Tom" Lee (Michigan), Leonard Stiel (Northwestern and Syracuse), Lloyd Sutterby (Wisconsin) and chairman George Preckshot (Michigan and Minnesota) were brought successively to UMC to provide the faculty for this program.

CRYSTAL-BALLING

WHEN ONE ASKS about the future, there is some head-shaking. The times are confusing and yet some important signals are showing "The future will be much more like the present than most people are willing to admit. Chemical engineering as a profession never looked better to me. How can we hope to attack problems in energy resources and supply (we better look at the consumption side of that equation, too), minerals and materials, food production and processing, environmental protection, etc., without bringing all of the physical and life sciences to bear on these problems. The only discipline in a University that offers most of these in a single program is chemical engineering. What a future! The major problem lies with the university itself, which now reflects society where every action and decision is politicized to the point where it cannot be recognized. Engineers are notoriously poor politicians and I fear we are in for rough times. University administrations want everything to appear democratic, so all faculty members are required to spend a major fraction of their time in their democratic responses which are swallowed up instantly by a political expedient. *Two extreme paths are open: either a small number of faculty will serve the administration as advisers and the rest of the faculty will be permitted to work with students, or we will see the management (administration)—labor (faculty) relationship of the industrial model prevail. The former is untested, but probably the best model for a university. The industrial model has been tested over many years and is often found wanting. Only a very few great men are willing to risk an unknown, even if it has a high return potential, so I expect to see the industrial model prevail in academia. Keep your productivity up and your costs down, but how are we going to convince a B.S. graduate he is only one more unit from our production system?*" □

NEBRASKA'S INTEGRATED PROCESS DEVELOPMENT/DESIGN LABORATORY

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SEEMINGLY MOST RESISTANT to change in the wave of innovation that has been so well documented in this journal is the traditional unit operations laboratory. Typically rather set experiments are conducted by two or three-man teams on fairly large pieces of equipment, followed by the submission of formal reports. There are obviously some advantages inherent in this format. Turning valves and watching apparatus approach steady state are good experiences for any chemical engineering undergraduate, and exposure to technical report writing has value. On the other hand, this type of exercise has limited flexibility. The equipment can be operated in only so many ways, and a file of previous years' laboriously written reports effectively squelches much new thinking by even the best of students.

Until 1969 Nebraska had a three-credit senior laboratory course in much this mold, with wetted wall and packed column mass transfer, concentric pipe heat transfer, and vapor-liquid equilibrium experiments. (Distillation and evaporator exercises had previously been abandoned.) In addition there were junior transport and senior process control laboratories, each for one credit. With the exception of the process control course, which featured nearly all modular equipment, we were encountering the same lack of enthusiasm and originality seen elsewhere.

This was probably sufficient to dictate a change, but we had yet other reasons. Our department has a strong tradition in thermodynamics and vapor-liquid equilibrium and therefore offers 1½ terms of them and only about one-half term of kinetics. The increased emphasis on kinetics in the last few years encouraged us to offer more, but we did not want to de-emphasize a strength at the same time.

These factors suggested to us that a laboratory sequence stronger in kinetics that required more

originality from our students would distinctly strengthen our curriculum. Properly formulated, this sequence could serve as a wrap-up to our whole program in that previous material could be re-emphasized, and could in addition give our students a taste of industrial problem-solving. The last point was especially important to us, because Nebraska is a primarily agricultural state and few students have any contact with either industry or engineers.

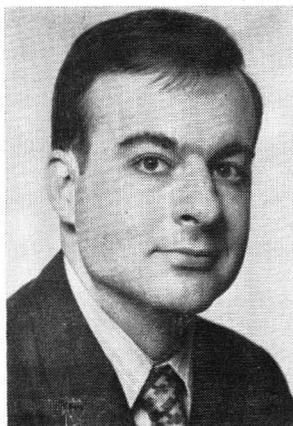
NEW SEQUENCE

THE BEST METHOD to achieve these goals seemed to be replace the unit operations and transport laboratories and a three-credit design and economics workshop course offered to second semester seniors with a two-semester, seven-credit, integrated laboratory and design sequence. This sequence was conceived to allow seniors to employ their own experimental data, along with those they could estimate or find in the literature, to achieve a preliminary design of a plant producing some simple but commercially unavailable chemical. Laboratories and design sessions were to be fairly free-form, specified laboratory times being necessary only because some equipment had to be used by more than one group. Equipment was to be simple, essentially glassware with some mixers and small metering pumps. Faculty were to serve primarily as consultants and were not to specify either experiments or treatment of data.

We fully believe in the advisability of asking students to provide their own direction, even though wasted time and poorer experiments and designs result from it.

Peter J. Reilly received an A.B. in chemistry from Princeton and a Ph.D. in chemical engineering from Penn. Before joining Nebraska, he was engaged in chlorocarbon and fluorocarbon process development at DuPont's Jackson Laboratory. His research interests are in the fields of fermentation and enzyme kinetics. (Below Left)

Delmar C. Timm was educated at Iowa State University, being awarded the Ph.D. degree in 1967. His industrial experience includes two years of polyolefin plant design. Professor Timm's professional interests are in process control and simulation, kinetics, and catalysis. He has authored articles in the area of population dynamics of polymerization and crystallization systems. (Below Right)



James M. Eakman received both his B.S. and Ph.D. from the University of Minnesota. He worked in the area of process research for Archer-Daniels-Midland and Ashland Chemical Co. before coming to Nebraska in 1968. His teaching and research interests include process engineering, computer aided design, optimization, and statistical computations. (Above)

students from discovering the process in the literature.

The only totally fixed feature was a weekly one-hour economics and design lecture during both semesters.

After piloting this concept with a group of six volunteers during the academic year 1969-1970, we have offered this laboratory sequence to the last four senior classes. In each year the specified product has been an ester, hexyl caprylate for two years; ethylene glycol dipropionate for one year; and 2-ethylhexyl oleate for two years (Table I). While the whole class studies the same reaction, groups are assigned different catalysts and operational modes to investigate so that little duplication in experimental systems occurs.

These systems were picked with several factors in mind. First, they were safe in that they were liquid at ordinary temperatures and were not flammable or explosive. Second, the kinetic mechanisms were known but were fairly complex. Third, there were problems in separating products from reactants—heterogeneous azeotropes in the first and third systems and a homogeneous one in the second. In addition, while the raw materials were fairly inexpensive, the products were not made commercially in large amounts. In fact, it is quite possible that we were the largest producers of one or the other. This prevented our

Table I. ESTERIFICATION SYSTEMS

<u>ALCOHOL</u>	<u>ACID</u>	<u>PRODUCT</u>
n-Hexanol	Octanoic acid	Hexyl octanoate
Ethylene glycol	Propionic acid	Ethylene glycol Dipropionate
2-Ethylhexanol	Oleic acid	2-Ethylhexyl oleate
<u>CATALYSTS</u>		
None		
Dibutyltin oxide		
Sulfuric acid		
p-Toluenesulfonic acid		
Strong acid ion exchange resin (amberlyst 15)		
<u>OPERATIONAL MODES</u>		
Continuous		
Batch		

Groups are expected to obtain kinetic data in approximately ten experiments to fit a model that is applicable at different temperatures, catalyst concentrations, and reactant ratios. This is, of course, a tall order for such a few runs, and any model obtained is admittedly only very roughly accurate; but we have found that there are diminishing benefits to the students by prolonging this line of attack any further. This rather draconian limit puts a great premium on a proper choice of experimental conditions for each run. We have become exceedingly hard-nosed in expecting a plan

to be formulated before any experimentation begins, though we realize that changes often are necessary after some data have been gathered.

This kinetics investigation occupies virtually the whole first semester. The second semester is devoted to vapor-liquid or liquid-liquid equilibria, originally an experimental project where data from each group were pooled, but more recently where the behavior of each system was estimated; physical properties, now also estimated or found in the literature; and the plant design itself. To add a bit of realism to the design, each group is

Seemingly most resistant to change in the wave of innovation, is the traditional unit operations laboratory.

required to choose a specific plant location within Nebraska. Our more adventurous students occasionally interview chambers of commerce and take pictures of available buildings and land. We do find, however, that often plants locate near the students' home towns rather than at the most advantageous location. The State Department of Economic Development has been extremely cooperative in this venture, providing literature on sites and lectures on factors that are important in the choice of a location.

STUDENT PERFORMANCE

SINCE THE MAIN GOAL of any curricular change is to increase knowledge learned and retained by students, this sequence must ultimately be judged on these grounds. How have our students done since the curriculum was changed?

Performance is appreciably better than in the old arrangement. Participants now are challenged to use kinetics, distillation and extraction design, vapor-liquid equilibrium and thermodynamics. Often they must go beyond classroom knowledge, for instance when confronting multicomponent distillations that behave in a highly nonideal manner. They have found that sophisticated computer methods are a great aid in design and optimization. While often they can obtain computer programs already written, on many occasions they have had to do their own programming.

Students are confronted with the concept of using their experimental data further. We would like to believe that this causes them to be more careful and more complete, but we notice that in many cases data are not yet fully trustworthy. This is partly due to the use of equipment for specific purposes for which it was not necessarily designed, inadequate analytical methods, and a general lack of time.

Undoubtedly more work is expended. Most of it is gainful, but some is wasted through improper choice of experiments, uncertain data, and lack of proper data-collecting. We expected this when we refrained from specifying experiments. To some extent the wasted motion is beneficial, in that it emphatically teaches the lesson that proper preparation ultimately saves time.

We do not claim that the students are fully happy at all times over the change. They realize that they are working harder, and they have several specific complaints in addition. Most deal with the intentional formlessness of the sequence. They would like more faculty direction and equipment more specifically designed for the experimental program. They are quite upset when work does not immediately lead to useful results.

We fully believe in the advisability of asking students to provide their own direction, even though wasted time and poorer experiments and designs result from it. This sequence is quite a change from their other laboratories and lecture courses, which are highly structured, and we expect them to be quite discomfited.

The new sequence provides the opportunity for procrastination, especially during the beginning and middle of the second term when the initial enthusiasm has disappeared and the task appears endless. We partially combat this by requiring periodic reports (Table II) and by informal questioning of results. This is a thin line to tread, since we want the students to provide their own direction.

Ironically, many groups are loath to seek faculty help or advice even when bogged down. Occasionally faculty initiative is required to open communications.

Students now are challenged to think independently, since very little information is being fed to them. If they are successful it is a strong prod to their self-confidence. Talks with graduates of this sequence leads us to believe that their prac-

(Continued on page 148.)



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COMPUTERIZED COST ENGINEERING IN THE PROCESS DESIGN COURSE

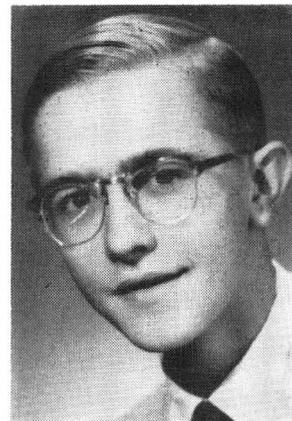
THEODORE W. CADMAN
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PRIOR TO TAKING process design, the chemical engineering student has been exposed to a variety of concepts and techniques in topic-specific courses such as calculus, thermodynamics, process control, transfer and transport phenomena. In many of these courses the subject matter and examples have been directed towards process equipment and process operations. But seldom has the student critically examined a processing system as a whole or quantitatively defined and investigated the objectives of a process design.

The design course serves as the stage for a concerted examination of processing systems and their objectives by the detailed analysis and appropriate aggregation of their component parts. This is customarily achieved through a series of selected design problems supplemented with classroom presentation of required background information and suitable generalizations as illustrated by the examples.

This is by no means a simple task and makes the design course one of the most challenging courses not only for the student but the instructor as well. As a result, comprehensive tools which can serve to reduce the time required for tedious manual calculations are more than welcomed.

It is in this vein that the computer has become a welcome ally during the past decade. Experience in the use of the computer for detailed calculations, simulation of the operation of individual equipment items, and the sizing of individual equipment items is now a common denominator of students entering design. In addition, a wealth of auxiliary programs for individual equipment items is available with many being of a sufficiently general nature for use in a design course. Moreover, significant advances have been made towards easing the completion of the tedious mass and energy balances for



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processes as a whole as PACER, CHESS, FLOW-TRAN, and similar programs amply illustrated.

One area has, however, been noticeably absent in the spectrum of computer-aided design techniques available for education-cost estimating. All too frequently, unexcelled sophistication is used in determining mass and energy balances and in sizing equipment; while cost estimating is left as a last minute effort relying on a list or graph of approximate values. Time and students' interests simply do not jive with the intricacies of manual cost estimating. As a result, short cuts are made in what is certainly one of the most significant aspects of design.

It is the objective of this paper to illustrate that this need not be the case. In particular, the potential role of a user-oriented cost estimating program, COST®* (*Cost Oriented Systems Technique*), in the design course is examined. Experience has indicated that computerized estimating can minimize the drudgery of cost estimating while providing a more definitive approach to estimating than can be obtained from all but the

*COST is a service mark of Icarus Corp. registered with the U.S. Patent Office.

most detailed manual estimate. Computerized estimating is thus an ideal candidate for raising the overall integrity of the process design course through rapid, convenient, and consistent cost estimating; particularly if the system is user-oriented and is designed to assign reasonable default values to unspecified data.

BRIEF DESCRIPTION OF COST®

The COST® system was developed for use by industry for the rapid estimation of chemical processing plant investment requirements. Currently over 50 firms use the system for this purpose.

In structure, the system consists of equipment cost models¹ for over 250 separate items ranging from agitated open tanks to water cooling tower systems. Each cost model simulates the steps involved in fabrication and installing of the equipment as closely as is feasible to yield as applicable:

- Fabrication material requirements,
- Fabrication labor requirements,
- Overhead and general and administrative expenses,
- Vendor or sub-contractors profit,
- Labor and material requirements for installation.

Using a data base covering the rates of some 300 materials of construction, 38 trades crafts, the purchased and installed cost of each equipment model is obtained.

The system allows for three levels of input data: minimum design input; maximum design input; and maximum cost input. The user selects the appropriate category on the basis of data available to him and required by the system as outlined in the User's Manual.²

To provide but one example, consider the use of the system for estimating the cost of a heat exchanger.

A card is prepared that details the minimum design input and range of acceptable design information for several of the types of heat exchangers handled by the system. In each case, as well as for all other models, only one card is required to specify the minimum design input of one equipment item.

Arbitrarily choosing a U-tube exchanger and a fixed tube sheet exchanger for examples and specifying material of construction, heat transfer area, and tube pressure, the results are automatically obtained upon accessing the system. A number of additional design parameters can be

reasonably chosen by the system and the purchased and installed cost as well as material and labor breakdown for installation can be provided for examination. Analogous user-oriented instructions and results can be incorporated for the cases of maximum design input and maximum cost input. Rapid review of the results is easily accomplished and the user can readily determine whether he should modify or further specify his design by comparing his data with the reasonable default values chosen by the system.

The system provides for the aggregation of equipment models into operational units and operational units into a total plant. Provisions are made for the specification of additional design data for each aggregation either by the user or by reasonable default values chosen by the system. The values chosen or computed by the system are clearly indicated for review and potential modification by the user.

TABLE 1
Table of Contents Illustrating Scope
of COST® Report

TABLE OF CONTENTS

Estimated Capital Cost
Master Summary
Operational Unit Summary
Material Component Cost
Labor Component Cost
Labor Component Manhours
Field Labor Summary
Engineering Cost Breakdown
Construction Overhead
Maintenance and Operation Data
Equipment List By Unit Operation/Process Separation

The output of the COST® system is designed in the form of a concise report containing the items illustrated by the Table of Contents in Table 1 obtained for a small plant. Particularly

All too frequently, unexcelled sophistication is used in determining mass and energy balances and in sizing equipment, while cost estimating is left as a last minute effort relying on a list or a graph of approximate values.

convenient are the number of summary tables given in the report. Among the most useful for a process design course is the Master Summary detailing the items contributing to the total fixed capital cost of plant.

PROCESS DESIGN COURSE OUTLINE

THE TYPICAL DESIGN problem requires consideration of a number of basic elements including:

- Process configuration
- Material and energy balances
- Equipment design and sizing
- Equipment costs
- Installed process cost
- Projected market and selling price
- Operating costs
- Estimation of profit.

Most students enter design with an extensive background in completing mass and energy balances, preliminary equipment design, and sizing of key equipment parameters. Background in the other areas is generally minimal, although a co-current process economic course is frequently taken with design.

Faced with the scope of design and the students' backgrounds, the instructor seeks to satisfy four principal aims in his outline of the course:

- Integrate and unify the student's process step-oriented background so as to be most applicable to the analysis of full scale systems
- Provide supplemental information on the elements of process cost, market, and profit estimation
- Provide a technically sound and usable summary of procedures for evaluating all the elements in a design, and
- Encourage the student to exercise his ingenuity in investigating alternate process configurations so as to maximize the profit of the overall operating system.

These aims can be most satisfactorily attained by continual emphasis on the totality of the design and by a judicious combination of lecture, outside reading, design assignments, and in-class discussion. Table 2 presents a brief outline of such an approach for a 16 week-3 hour/week course.

The outline suggests a total of five design problems to be completed by each student or group.

The first problem is designed to mesh in a definite manner with the students' background. Lectures, in-class discussion, and outside readings and references are used to indicate the

scope of design and supplement the background of the student in the areas of mass and energy balances and preliminary equipment sizing. Emphasis is also given to sources of physical property data and alternate design methods.

TABLE 2
Process Design Course Outline
(16 weeks, 3 hr/week)

Week	Item
1	<p>Lecture: Elements of a design, role of students' background; Sources of additional physical property data; Sources of additional equipment design models.</p> <p>In-Class Discussion: Review of a completed design report; Review of material for design problem #1.</p> <p>Assignment: Design Problem #1 (Formulation) Mass and energy balances; Preliminary equipment sizing.</p> <p>Typical Outside Reading and References:</p> <p style="text-align: center;">TEXT</p> <p>Peters and Timmerhaus, Plant Design and Economics for Chemical Engineers Ch. 1, 2, 3, and 12</p> <p style="text-align: center;">PHYSICAL PROPERTIES</p> <p>Perry's Handbook, Hydrocarbon Processing; Reid and Sherwood, Properties of Gases and Liquids; Smith and Van Ness, Introduction to Chemical Engineering Thermodynamics; International Critical Tables</p> <p style="text-align: center;">EQUIPMENT DESIGN</p> <p>Peters and Timmerhaus, Ch. 13, 14, and 15; McAdams, Heat Transmission; Treybal, Mass Transfer Operations; B. D. Smith, Design of Equilibrium Stage Processes; J. M. Smith, Chemical Engineering Kinetics; Bennett and Myers, Momentum, Heat, and Mass Transfer</p>
2	<p>In-Class Discussion: Review of Problem Areas Encountered in Design Problem #1</p> <p>Lecture: Supplemental as required Discussion of Process Alternatives</p> <p>Assignment: Design Problem #1 Solution and Preparation of Report</p> <p>Outside Reading and References: Supplemental as required</p>
3-4	<p>Lecture: Elements of Process Economics Equipment Costs (Manual Estimation); Plant Costs (Manual Estimation); Profit Projection</p> <p>Assignment: Design Problem #2 Manual estimation of plant costs and profit</p> <p>In-Class Discussion: Review of Design Problem #1; Review of Progress and Difficulties in Design Problem #2</p> <p>Outside Reading and References:</p>

The design course serves as the stage for a concerted examination of processing systems and their objectives by the detailed analysis and appropriate aggregation of their component parts.

TEXT

Peters and Timmerhaus, Ch. 4 to 11

REFERENCES

- Happel, Chemical Process Economics; Shreve, Chemical Process Industries
- 5-6 Lecture: Computerized Cost Estimation Structure of Program Use of COST®
Assignment: Design Problem #3 Estimation of Profit using COST® as a tool
In-Class Discussion: Review of a completed COST® estimate; Practice session of use of Program; Review of Design Problem #2; Analysis of Design Problem #3
Outside Reading and References: COST® System Users Manual
- 7-12 Assignment: Design Problem #4 Comprehensive Design
Lecture, In-Class Discussion, Outside Reading and References: Chosen to suit selected problem
- 13-16 Assignment: Design Problem #5 AIChE Student Contest Problem
Lectures, In-Class Discussion, Outside Reading, and References: Supplemental information not conflicting with rules established by AIChE for the Student Contest.

The second design problem emphasizes the manual estimation of plant costs and profit. Primary emphasis is given to the elements which collectively define these items.

The third design problem emphasizes the estimation of equipment costs and total fixed capital costs. The structure of the system is discussed and the use of the system is taught in class during a three hour practice session. The role that the program can play in the development of a total design is emphasized.

The fourth design problem is a comprehensive design problem covering all important aspects. A high degree of interaction is maintained, group solutions are encouraged, and in-class review and constructive criticism are continual.

The fifth design problem is a comprehensive design completed on an individual basis. The AIChE Student Contest Problem, completed by the individual under the rules established for the contest, is an excellent example of the class of problem recommended. Other course material

may be devoted to reviews of selected design advances which do not conflict with the individuality desired in this final design problem.

COMPUTERIZED COST ENGINEERING

AS IMPLIED BY the course outline given previously, a computerized cost estimating system such as COST® can be used to reduce the drudgery of cost estimating in the design course and permit additional emphasis to be placed on the design aspect itself. The estimating system can be designed so as to provide numerous advantages:

- The estimates are quite definite, are concise, and are consistent.
- The input data is easy to prepare, requiring only certain critical size parameters to access the system.
- A comprehensive set of reasonable default values are chosen for data not supplied and concise output details the assumptions made.
- The output is concisely prepared and highly user-oriented.
- The detail of the output encourages the student to investigate labor/material relationships, purchased versus installed cost, and the effect of design parameters on cost and subsequently profit.

In every respect, this approach has been found to offer to the student a more comprehensive cost estimate than he could ever be expected to prepare and to offer it at only a fraction of the time he would ordinarily have devoted to less definitive techniques.□

REFERENCES

1. H. G. Blecker, Simulation of Chemical Processing Plant Investment by Computer, Presented at 1972 SSC.
2. H. G. Blecker and T. M. Nichols, *COST® System Users Manual*, ICARUS Corp., Second Edition, Jan. 1973.

ACKNOWLEDGEMENT

The author expresses his gratitude to Mr. Herbert B. Blecker, President of ICARUS Corp., for making the course at the University of Maryland. Inquiries should be directed to: Director of Technical Services, ICARUS Corp., 8630 Fenton Street, Silver Spring, Md. 20910. The classes of '72-'73 are also acknowledged for their zeal and patience with the experiments of the author.

THE USE OF FLOWSHEET SIMULATION PROGRAMS IN TEACHING CHEMICAL ENGINEERING DESIGN

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The chemical engineering design student is required to calculate the material and energy balance, the size and cost of equipment, the operating cost, and some profitability criterion for each process he studies. Once the student has mastered these procedures by hand computation, repetitive calculations become monotonous and time consuming. The result is that often little time is available for the study of design principles.

A computer flowsheet simulation program, named CHESSE, has been developed at the University of Missouri-Rolla that does the above calculations and provides the user with the profitability of the simulated process. The development of the CHESSE program is discussed and several examples of processes simulated by design students are presented.

The use of CHESSE during the latter part of the design course has been found to enhance the student's education in this area. Additional cases can be studied in synthesizing and analyzing the optimal process and a better grasp by the student of design principles is apparent.

THE PROCESS OF EDUCATING chemical engineers culminates in the design course. This course requires the student to apply the basic technology from other courses, such as thermodynamics and transport operations, to predict the performance and economics of chemical systems.

Students often realize, for the first time in the senior design course, the practical application of much of the course content of their undergraduate curriculum. It is, therefore, essential that the design course be a comprehensive integration of technological principles from earlier courses with design and economic procedures.

Comprehensive design coverage represents a challenge to educators who must often accomplish this coverage in three semester hours. Consequently, new and innovative methods are constantly being sought to improve the teaching efficiency.

One innovative teaching technique is the use of flowsheet simulation programs for the solution to classroom design problems.

FLOWSHEET SIMULATION PROGRAMS

ONE SUCH INNOVATIVE teaching technique is the use of flowsheet simulation programs [1,2] for the solution to classroom design problems. These programs define the chemical process material and energy balances from a description of the equipment in the process [3].

A typical design problem is the ethylene process [4] shown in Figure 1. Ethylene is produced by cracking ethane and propane. The product is purified in three distillation columns. Hydrogen and methane are recovered for fuel, and ethane is recycled. Propylene and heavier hydrocarbons are by-products.

The material and energy balance data for the ethylene process are shown in part in Figure 1. These data could be obtained by hand calculation or a flowsheet simulator could be employed to provide this information.

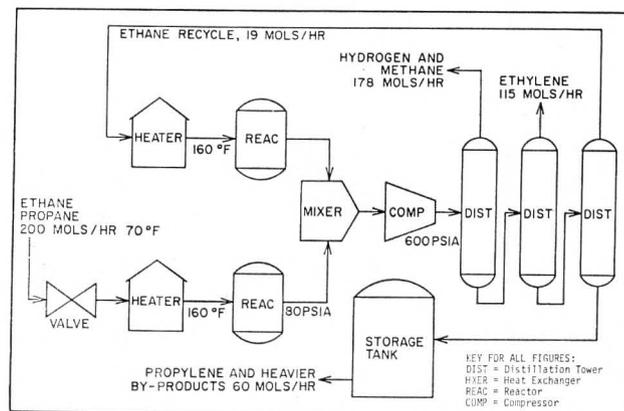


FIGURE 1. SIMPLE ETHYLENE PLANT [4]

The design student must proceed, exactly as would the computer, in calculating material and energy balance relationships for such a process. Once the basic concepts are understood by the student, these calculations become routine and time consuming. Thus, the use of a simulation system removes some of the monotony from the design course and allows more emphasis to be placed upon the principles of design. The incorporation of flowsheet simulation programs in teaching design has been practiced for many years at several universities [5].

Design, of course, does not stop with the material and energy balance, but culminates with economic analysis of the process which leads to an optimal design [2]. In making an economic analysis, the student is required to make detailed estimates of the equipment and operating costs in the process. The procedure of cost estimating must be repeated for each case studied in arriving at the optimal design. Again, such procedures are routine, time consuming, and afford little learning value to the student.

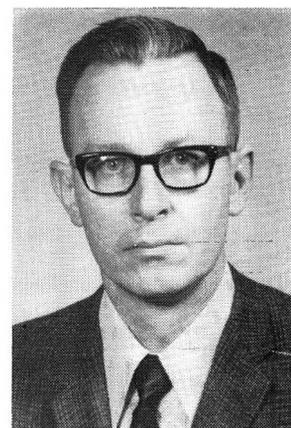
The University of Missouri has developed a simulation program, named CHESSE (*C*hemical *E*ngineering *S*imulation *S*ystem with *E*conomics), [6] which does the cost estimating and provides a complete economic analysis of the chemical process. This program is a modification of the basic CHESSE system [4]. The purpose for developing such a program was to enhance the teaching of design. Several advantages were expected:

- Provide the student the opportunity to study more processes.
- Provide the student the means of arriving at a better design since more cases can be studied in searching for the optimum.
- Introduce the student to computer oriented design methods used by industry.

The purpose of this paper is to discuss the development of the CHESSE program and to report on its use in teaching design. A basic understanding of flowsheet simulation programs by the reader is presumed.

CHESSE

Economic analysis is the determination of some economic criterion, such as return on investment, that can be used to judge the worth of the system under study. The choice of the best process *design* is made by reviewing the economic criterion for all processes studied and choosing the process that maximizes the profitability. The basic



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information required for calculation of an economic criterion is the investment and profit.

The economic calculations can be done on the computer and are easily integrated with the usual flowsheet simulation programs which provide much of the data for the economic balance. The computations can best be done in a stagewise manner. First, the material and energy balance must be converged for all recycle loops. Then the plant investment, which is dependent upon the material and energy balance, can be determined. Finally, the profit, which depends upon the investment as well as the material and energy balance data, is found. The procedures used in CHESSE to find the investment and profit will be summarized.

DETERMINATION OF INVESTMENT

The total investment for a chemical process is made up of the cost of the process equipment plus the cost of auxiliary facilities, such as the supply of utilities. The auxiliaries cost can generally be calculated as a function of the investment in process equipment. Therefore, the total investment can be found from the size and cost of each individual item of equipment within the process.

The basis for sizing and costing the equipment in the CHESSE program is given in Table 1. Most of the data for these computations is available from the material and energy balances and only a minimum amount of additional information must be supplied by the student.

The cost calculations for each equipment item

TABLE 1. SUMMARY OF DATA FOR DETERMINATION OF EQUIPMENT SIZE AND COST IN CHESSE

Equipment	Cost Basis	Design Basis in CHESSE	Data Source
Distillation Tower	Tower height, diameter, material of construction, and type of trays	Number of trays by Fenske, Underwood, Gilliland procedure [7]. Tray by tray determination also available. Tray spacing set at 2 ft. Tower diameter by maximum vapor velocity method of Souders and Brown [8]	Reflux ratio, type of tray and material of construction by programmer. Flow rate and thermodynamic properties from CHESSE.
Absorber	Height, diameter, material of construction, and type of tray or packing	For packed columns, height based on absorption factor method [9], and diameter based on flooding velocity method of Lobo [10]. For tray towers diameter found as in distillation.	Programmer specifies type of column, material of construction. Other calculations by CHESSE.
Flash Column	Height, diameter, and material of construction	Three feet of liquid holdup provided. Three feet of vapor disengaging space provided. Diameter same as for distillation.	Flow rates and thermodynamic properties by CHESSE. Material of construction by programmer.
Heat Exchanger	Area, material of construction, number of passes and shells, and type exchanger	Area from heat duty, overall heat transfer coefficient and logarithmic temperature difference.	Heat duty and temperatures from energy balance. Coefficient and other data by programmer.
Reactor	Volume, material of construction, and type of reactor	None	Programmer must specify volume, material of construction and type of reactor.
Pump and Compressor	Capacity, type of pump and drive, pressure rise and material of construction	Work of compression calculated from specific heat ratio. Pump work from product of flow rate and pressure rise [4].	Programmer specifies pressure rise, type of material, and whether spare pump is needed.
Valve	Diameter and material of construction	Valve Diameter as pipe diameter to give liquid velocity of 4 fps or vapor velocity of 10 fps.	Material of construction specified by programmer
Tank	Volume and material of construction.	Tank Volume from flow rate and desired holdup.	Flow rate from material balance. Holdup and material of construction by programmer.

are based on the modular cost concept of Guthrie [11]. The cost computed is the total installed cost including foundations, piping, wiring, instrumentation, etc. For each piece of equipment, the cost depends upon the equipment size, material of construction, pressure, and specific type, such as steam or gas fired heat exchanger. The size is computed by CHESSE from the appropriate flow rate and design equation. Pressures are available from the energy balance. The programmer must specify equipment type and material. Options are available for the programmer to specify the cost separately for any piece of equipment, if the methods for costing in CHESSE are not appropriate. All costs in CHESSE are from 1970 data and provision is made to adjust these costs to the present time by use of the Marshall and Stevens Index [13].

The total process equipment cost is found by adding the costs for the individual items of equipment in the process. Auxiliary equipment costs are then found according to the percentages given in Table 2 [12]. These percentages total about 40 percent of the process equipment cost, and the programmer may change this percentage, if de-

sirable. CHESSE assumes a Gulf Coast location and a location factor is provided for adjusting the cost for a difference in geographic location. Contingency is then added to give the total investment. A contingency of 10 percent is added by the program, but the programmer has the option of varying this percentage.

REVENUE, OPERATING COST, AND PROFIT

The basic data for the determination of revenue and process operating cost in CHESSE is summarized in Table 3. These data are computed from the total investment and material and energy balance information.

The method of computation and the source of the data are also given in Table 3. Revenue and raw materials cost are calculated from the product and input stream flow rates supplied by the material balance. Stream prices are furnished by the programmer. Utilities costs are determined from the energy requirements and the prices for power, fuel, steam and water. Labor requirements are found from the Wessel correlation [14]. Other fixed costs are determined as a percentage of the

Table 2. Summary of Investment in Auxiliary Facilities for Chemical Process Plants

Auxiliary Facilities	Percentage of Installed* Process Equipment Cost Added [12]
Process Piping	20.0
Yard Improvement	
Land Cost	2.0
Site Clearing	0.6
Parking Areas	0.2
Landscaping	0.1
Yard and Fence Lighting	0.2
Other Improvements	0.4
Utilities	
Steam Generation	3.0
Steam Distribution	1.0
Water-Supply, Cool and Pump	1.8
Water-Distribution	0.9
Water Treatment	0.6
Electric-Main Substation	1.5
Electric-Distribution	1.0
Gas Supply and Distribution	0.3
Air Comp. and Distribution	1.0
Sanitary-Waste Disposal	0.3
Service Facilities	
Auxiliary Buildings	5.0
Railroads	0.6
Fire Protection System	0.7
Communications	0.2
Location Factor (Basis—Gulf Coast Location)	0.0
Contingency	10.0

*NOTE: Installed equipment cost includes equipment instrumentation, wiring, piping, minor steelwork, concrete foundations, substructures insulation, and painting.

total investment, labor cost or working capital. Cost items such as advertising, product distribution and research are computed as a percentage of revenue [12]. CHESSE uses industry wide average utilities prices or percentages to compute these costs. The programmer has the option of specifying values different from these averages, if desirable.

The total operating cost is the sum of the items, except revenue and working capital, given in Table 3. The before-tax earnings are computed as the difference between the revenue and total operating cost. Income taxes are figured as a percentage of the before-tax earnings and are subtracted from before-tax earnings to give net profit.

The cash accumulation is calculated as the sum of net profit and depreciation. CHESSE presently computes two economic criteria; return on

investment and payout period. The return on investment is the net earnings divided by the investment expressed as an annual percentage. The payout period is the investment divided by the cash accumulation.

If desired by the programmer, the investment and economic calculations in CHESSE can be bypassed entirely.

TEACHING EXPERIENCE WITH CHESSE

The experience with the use of CHESSE in the classroom has been encouraging. Several examples of the types of problems the students have solved will exemplify the kinds of results obtainable from a program such as CHESSE.

Ethylene Process

The ethylene process shown in Figure 1 was simulated by the design students using CHESSE. This plant was designed to produce 115 mols/hr of ethylene for 330 days per year, i.e., 25 million pounds per year. A total investment of \$1,008,965 is required. The investment summary of individual equipment items is also available from CHESSE.

A total operating cost of \$1,445,715 is computed. This represents a cost of ethylene of about 3.5 cents per pound, allowing credit for by-products. By comparison, Guthrie [15] gives the investment for this size ethylene plant as \$1,100,000 and the operating cost as 3.2 cents per pound.

With an ethylene price of 4 cents per pound, the return on investment is 6.2 percent per year and the payout period is about 7 years. From this initial design, the students proceed to evaluate the effects of larger plant sizes, product price and process variables on the economics of the ethylene process.

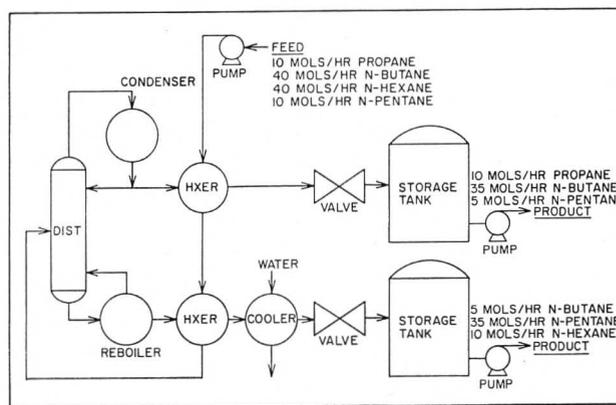


FIGURE 2. SIMPLE DISTILLATION PROCESS WITH HEAT RECOVERY

Simulation of this process requires about 20 seconds of computer time on an IBM-360-50 machine.

Hydrocarbon Distillation Optimization

A simple distillation column with heat recovery, shown in Figure 2, is used to illustrate optimization principles. The column splits a multi-component paraffin mixture and the products ex-

change heat with the feed. The process variables for optimization are tower pressure, column reflux ratio and approach temperatures in the heat exchangers.

Benzene Process

Figure 3 is a typical process for the hydrogenation of toluene to produce benzene. Hydrogen and toluene are heated to 1250°F and reacted at

TABLE 3. SUMMARY OF ECONOMIC DATA FOR DETERMINATION OF OPERATING COST IN CHESSE

Data	Method of Computation	Source of Data	Options
Working Capital	(5 percent of Investment) + (8 percent of revenue)[12]	Investment and revenue calculated by CHESSE	Other percentages may be specified by programmer.
Revenue	$\Sigma[(\text{Volume of product streams}) \times (\text{product prices})]$	Volume of product streams from material balance. Prices furnished by programmer.	
Utilities Cost			
Electricity	(Power consumed) x (\$.01/kwh)	Power consumption from energy balance.	Alternate unit power, fuel steam and water costs may be specified by programmer or programmer may specify utilities cost in any equipment item.
Fuel	(Fuel consumed) x (\$.30/mm BTU)	Fuel consumption from energy balance.	
Steam	(Steam consumed) x (\$.65/mm BTU)	Steam consumption from energy balance.	
Water	(Water consumed) x (\$.10/m gal)	Water consumption from energy balance.	
Raw Materials Cost	$\Sigma[(\text{Volume of Incoming Streams}) \times (\text{Prices})]$	Quantity of incoming streams from material balance. Prices specified by programmer.	
Operating Supplies	(6 percent of labor) + (catalyst cost)[12]	Labor cost from CHESSE. Catalyst cost by programmer.	Percentage may be varied by programmer.
Labor Costs	(Operating labor hours/yr) x (labor cost/hr)	Man hrs = $[\text{tons product}](10)(N) / (\text{Capacity, tons/day})^{.75}$ [14] where N = number of process steps. Capacity, production and number of steps found by CHESSE. Labor cost/hr of \$3.50 is used.	Alternate hours or cost may be supplied by programmer.
Supervision	20 percent of labor cost [12]	Labor cost from CHESSE	Percentage Variable
Payroll Burden	(.25) x (labor cost + supervision) [12]	Labor cost and supervision from CHESSE	Percentage Variable
Overhead	(.5) x (labor cost + supervision) [12]	Labor cost and supervision from CHESSE	Percentage Variable
Maintenance	5 percent of investment [12]	Investment from CHESSE	Percentage Variable
Taxes and Insurance	2.5 percent of investment [12]	Investment from CHESSE	Percentage Variable
Depreciation	$(1 - \text{Salvage Value}) \times (\text{Investment}) \div \text{Depreciable life}$	Investment from CHESSE. Salvage value = 10 % of investment	Salvage value and depreciable life are variable
Interest	(.1) x (Investment + Working Capital)	Investment and working capital from CHESSE	Percentage Variable
Sales and Advertising	15 percent of Revenue [12]	Revenue from CHESSE	Percentage may be varied by programmer
Administration	6 percent of Revenue [12]	Revenue from CHESSE	Percentage Variable
Product Distribution	3 percent of Revenue [12]	Revenue from CHESSE	Percentage Variable
Research and Development	10 percent of Revenue [12]	Revenue from CHESSE	Percentage Variable

The student should never use a computer unless he knows exactly what the machine is doing.

800 psia. The effluent from the reactor is separated by a series of flash and distillation towers. Hydrogen and toluene are recycled back to the reactor.

CONCLUSIONS

At the University of Missouri-Rolla the CHESSE program is not introduced into classroom use until about the middle of the design course. At this time, the student has been through several equipment design problems and at least one detailed process design by hand calculation. The procedures of making material and energy balances, sizing equipment, cost estimation, economic analysis, and optimization have been mastered. The use of CHESSE is not to teach these procedures, but rather to facilitate their use in learning design principles.

The use of CHESSE requires no special or prior computer programming skill. The NAME-LIST format is used to furnish all data for the program. These procedures are quite simple and the student usually is ready to design a process on the computer with a few hours instruction and practice.

During the second half of the design course, after CHESSE has been introduced, the student will design and optimize about three complete chemical processes, such as those shown in the earlier examples. The optimization may involve several variables and advanced optimization techniques are introduced. The class may work on the same process at one time, but each student can be assigned a different problem by changing the plant size or some other parameter of the system.

Students seem to enjoy the use of CHESSE. More importantly, they seem to obtain a deeper grasp of design principles. The economic effect of changing values of a variable become readily apparent. Important variables are more readily distinguished. The point of diminishing returns in optimization becomes real. Computer design permits study of areas, such as plant location and distribution costs, that do not receive much attention otherwise. Furthermore, the area of process synthesis can be stressed since the student has

more capability in the allotted time for modifying processes.

It is not implied that the CHESSE program provides the ultimate in design education. Many refinements and improvements are still needed. Improved thermodynamic capabilities, additional unit operations, more precise methods of equipment sizing, and better cost estimation are some of the areas that are under study.

The student should never use a computer unless he knows exactly what the machine is doing. Therefore, he should always be required to do process design calculations by hand. However, the subsequent use of computer aided design programs can be used to enhance his education. □

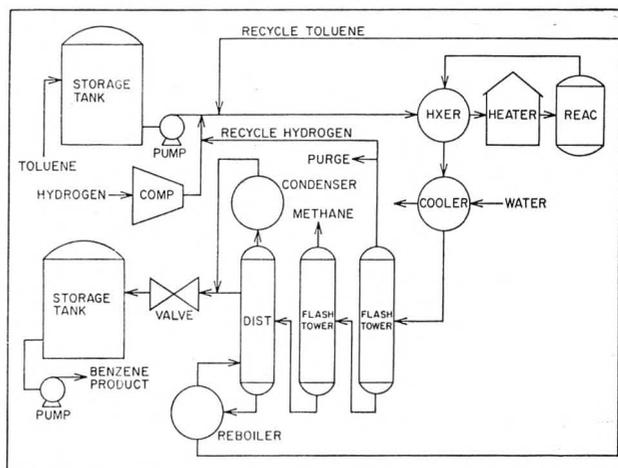


FIGURE 3. BENZENE PROCESS

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COST ESTIMATING BY COMPUTER IN PROCESS DESIGN

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CHEMICAL ENGINEERING education at Rensselaer includes process design in which the students design and evaluate complex chemical process components and systems through the application of scientific, technological, and economic principles. Emphasis is placed on problem formulation and the conceptual, analytical, and decision aspects of open-ended situations through integration of knowledge and skills gained in previous and concurrent formal course study. A significant part of the course relates process design to economics by such measures as return on investment and selling price. Probabilistic aspects¹ as well as conventional deterministic situations are treated. Although economics calculations are elementary, they require significant student time which could be better spent in synthesis and analysis. It is desirable for students to study economic consequences of production rate changes, manufacturing cost variations, depreciation methods, and other factors with a minimum of effort being expended in obtaining the information. To assist students in these analyses, a computer procedure to estimate annual rate of return for a chemical process was recently developed under two Master of Engineering projects.^{2,3} Although the procedure considers only the deterministic situation under a single set of circumstances, it has improved student efficiency in preparing and understanding the economics sections of process design reports.

FEATURES OF THE PROCEDURE

IT IS THE OBJECTIVE of the procedure to provide an annual rate of return on investment capital from estimates of capital and operating costs derived from equipment specifications; utility, product, and raw material rates and unit

costs; labor requirements and rates; on-stream time; and similar input information. The program, shown schematically in Figure 1, is organized into four levels of operation having the following functions: program control, input/output, basic calculations, and equipment cost data.

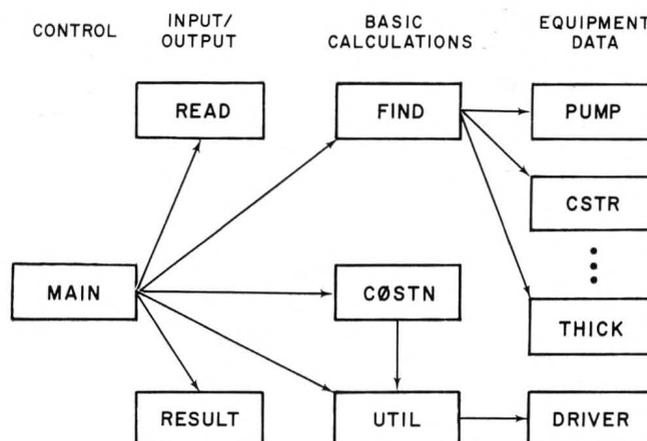


FIGURE 1
Organization of Process Economics Procedure

The executive routine MAIN directs the procedure by properly sequencing the routines of the second and third levels of program hierarchy. Each set of process specifications is considered as a separate case, and MAIN is responsible for array initializing and providing the required number of case studies.

Major data input is accomplished by READ. These data include specifications for the individual items of equipment, the current cost index, and general information concerning manufacturing costs: labor rates, utility rates, and on-stream time.

All equipment costs are determined in a general costing routine COSTN using the power-law relation

$$\text{Delivered Cost} = C_1 (\text{SIZE}) C_2$$

Five size ranges are available, and the coefficients C_1 and C_2 are transmitted from the

equipment routines PUMP, CSTR, . . . , DRIVER via COMMON block. Thus one general cost-determining procedure including logic for selecting the proper size-related power-law coefficients is used, resulting in an appreciable reduction in core requirements. Logic for accommodating equipment sizes outside the minimum and maximum size ranges is also provided. Access to these coefficients stored in the equipment routines is accomplished by the routine FIND.

All individual utility-related calculations are performed or controlled by UTIL. As its first function, the routine converts utility usage of each item as presented in the equipment specifications to an annual rate and cost, based on the on-stream time. Seven different utilities are considered: electricity, steam (three types), fuel, cooling water, and an undesignated utility to be specified by the user. The routine also accumulates individual costs by category for presentation in the final economic summary.

Control of capital cost determination for drivers is the second function of UTIL. If equipment specifications indicate a driver is required, the routine DRIVER is called to supply size-related cost parameters to the costing routine COSTN. The proper type of driver is determined by the utility specified.

Equipment data routines PUMP, CSTR, . . . , DRIVER are in a standard format and contain two types of data: a description of the equipment category, design, and construction material to be printed as output; and power-law coefficients and size limits for the costing routine COSTN. Each item of equipment is specified by 25 input parameters which are summarized in Table 1 and which determine the options within the data routine to be used. The size-related cost coefficients and size limits were adapted from the compilation of Dryden and Furlow⁴ and other sources. Forty equipment categories are available in the procedure: Conventional processing equipment including pumps, heat exchanges, pressure vessels, etc. —24. Unspecified processing

A computer procedure has improved student efficiency in preparing and understanding the economics sections of process design reports.

Emphasis is placed on problem formulation and the conceptual, analytical and decision aspects of open-ended situations.

equipment —1. Specified drivers —3. Unspecified driver —1.

The two unspecified categories for processing equipment and drivers permit direct input of capital costs obtained external to the program.

A process comprising of fifty items or less of processing equipment (excluding drivers) can be accommodated by the procedure. Spares or identical items can be specified by parameters and are not included in this limitation.

The economic analysis is performed in RESULT, a general bookkeeping and output routine. Manufacturing fixed capital is determined from delivered equipment costs and equipment Lang factors with cost adjustments by the current cost index. Nonmanufacturing fixed capital is estimated from the manufacturing fixed capital, and working capital items are provided as input.

TABLE 1. Equipment Parameters

1. External reference (refers to flowsheet item number)
2. Internal reference (designates equipment subroutine called)
3. Construction material option
4. Size parameter
5. Utility type
6. Utility usage (as power)
7. Design option
8. Pressure
9. Temperature
10. Number of identical pieces
11. Utility usage (as flow rate or other)
12. Material flow rate
13. Driver flag (determines if driver is required; utility type determines driver type)
14. Size parameter
15. Size parameter
16. - 22. Unassigned.
23. Driver cost if not calculated in subroutines
25. Installed equipment cost if not calculated in subroutines

Additional input information required for manufacturing cost estimation include flow rates and costs for raw materials, product, and by-products, and the labor requirements. The final economic

analysis is summarized as six tables:

- Equipment specifications and cost details.
- Delivered equipment cost summary.
- Utility cost summary.
- Capital (manufacturing, nonmanufacturing, and working) investment summary.
- Manufacturing (chemical, utility, labor, overhead, maintenance, etc.) cost summary.
- Annual earnings and rate of return summary.

Additional tables summarize input information.

The procedure, written in FORTRAN IV, occupies approximately 74K bytes of storage comprised as follows:

Equipment data routines	22K	
Operation routines	17K	
Total program		39K
FORTRAN compiler routines	30K	
Computer operating area	5K	
Support		35K
Total core requirement		74K

The procedure operates in batch mode from disc-stored object code, and a typical plant containing 25 major items of processing equipment is cost estimated in 10 seconds or less using an IBM 360/50 computer.

APPLICATION IN PROCESS DESIGN COURSE

THE PROCEDURE WAS implemented on a trial basis in the senior process design course at Rensselaer during the spring semester of 1973. After several instructional periods on concepts and methods of process design economics, a one-hour lecture was presented on the structure and operating procedure of the costing program. This was supplemented with a hand-out describing specific details:

- Summary of procedure for estimating capital requirements and manufacturing costs.
- Outline of equipment specification elements (an extension of Table 1).
- Specifications required for each item of equipment available in the equipment routines.
- Detailed format for input data.
- JCL instructions.
- Input and output for a sample problem.

Students applied the procedure during the design and analysis of a solvent recovery facility, a conventional design problem assigned for seven weeks. Class-supplied instructions for the program appeared satisfactory, and no further instructions or assistance were required.

In this limited application, the procedure was successfully used. Output records, detailing the

economics of the design, were directly incorporated into the final design reports. As use of the procedure was experimental, its use in parametric economic studies was not considered. This initial success will encourage more extensive use in future classes.

CONCLUSION AND FUTURE WORK

IN ITS PRESENT FORM, the procedure was successful in preparing the economic analysis of a typical chemical process based on an annual rate of return on investment in a deterministic situation. This is a somewhat limited case, so future development will be conducted in two areas. One area of endeavor will consider restructuring the input/output procedures and control concepts so the program will accommodate several optional economic analyses (e.g., selling price determination) as well as probabilistic situations described earlier. A second effort has as its objective the adaption of the procedure for interactive use with a teleprocessing system. Thus both batch and conversant modes are projected for future operation. □

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TEACHING PLANT DESIGN TO CHEMICAL ENGINEERS

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FOR THE PAST TWELVE years, the Department of Chemical Engineering at Mississippi State University has taught plant design in an atmosphere similar to that which a process engineer encounters in industry. The professor utilizes his twenty years or more of industrial experience (a large percentage of which was directly involved with plant design, expansion and bottleneck removal programs in large industrial plants and petroleum refineries) to teach this course in a practical manner. The principal handicap has been the three credit hours of time allotted in the curriculum for such an important course, a disadvantage experienced by most schools due to so much material being squeezed into a four year program.

OBJECTIVE AND TEACHING METHOD

The principal objective of the course is to train engineering students to apply the materials presented in other college courses to the practical solution of one large plant design problem. A problem in design must be selected from a large list of possible chemical plants that will require a great deal of thinking and application of graphics, mathematical and chemical knowledge, mass and energy balances, thermodynamics, unit operations, and kinetics in the solution of the problem. In addition, the students are required to consider the instrumentation and the practical application of economics by having to make an economic appraisal of the proposed investment when the plant is assumed to operate at 80, 100 and 120% of design capacity.

Another objective is to aid the students in the transition from college courses to industrial work. It is believed to do their best, the students must be exposed to conditions similar to those they generally encounter in industry. The three credit-hour course at this institution is divided into a one hour lecture and a six hour continuous design

period. The objective of this long design period, consisting mostly of desk and library work, is to permit the students to adjust to a longer period of concentration as experienced in industry. This longer period is better also, because it allows them to spread their design instruments and data out onto a drawing board. And it reduces the percentage of time utilized in getting settled down to work and of getting ready to leave which takes place when equal time is distributed over two design periods.

The students are encouraged to visit the professor in his nearby office when they need help or they may be permitted to visit some other professors on the staff that may have some specific experience or data that would be helpful in the solution of some particular phase of their problem. Students have the same degree of freedom of visiting other areas of the campus as the need arrives by simply signing out as to when they left and where they may be located. They are highly discouraged from returning to their living quarters for more than enough time to pick up something they may have left behind. They are to remove their name from the register when they return to the building. This record is normally kept in one corner of the blackboard where it can easily be seen by all. This serves about the same as leaving word with an office secretary or group leader in industry. The students are given a list of chemical plants from which they may choose one to design. Each group of three students works on a separate problem. A group of three was chosen for advantages in training in human relations; and because there is plenty of work assigned to keep three people

We teach plant design
in an atmosphere similar to
that which a process engineer
encounters in industry.



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busy. A group of four generally does not work out well because they often work too much in pairs and create disciplinary problems with each set competing or griping about the other two's work or the like; or one student acting like an outcast and going his own way—most commonly goofing off and not doing his share of the work.

The one hour lecture is devoted to informing the students of the general information they need to know to follow the next progress step-wise procedure as outlined in the "Plant Design Instruction Manual," a book of approximately 215 pages written by the professor. The course is divided into six steps and each step is terminated by a progress report. The six major progress reports are divided-up into progress steps as follows:

PROGRESS REPORT 1—

Selection of Process Route

A literature survey is conducted of the possible routes that could be selected to produce some chemical or group of chemicals that are used in industry on a large scale. A list of about 50 or more are given to the students to choose from, or they may select something based on knowledge they have learned in summer work or in the co-operative program. Students often have made a literature survey and know what they wish to work on when they register for the course.

The students are expected to make block flow

diagrams of all the routes that have been used on a commercial basis as revealed by the literature search and describe the process in a general manner. Then they select one of the routes and give their reasons for selecting that particular route over the other ones.

PROGRESS REPORT 2—

Process Flowsheet

This involves the layout of a detailed process flowsheet using typical symbols for the equipment for the battery unit. Each stream is numbered with all major equipment, such as pumps, condensers, exchangers, reboilers, etc., shown. A heat and material balance is required over the overall plant as well as the individual pieces of equipment. The size range, feed, and product series qualities for the plant are set by the professor and differ from any other previously designed plant, but are comparable in sizes to those being quoted in the construction box score reported in the literature. Utilities are generally assumed to be available in the complex operated by the mother company. The unit cost figures placed on these utilities are selected for the region of the country where the plant is to be located (usually the Gulf Coastal region, in our case).

PROGRESS REPORT 3—

Site Selection, Plot Plan

This involves the selection of a plant site, assuming the selection has been narrowed down to one area in each of three states. Then students make a plot plan layout of an assumed plant complex using blocks for office buildings and battery limit units other than the battery limit plant under design. The specific plant being designed has a plot layout of all the major equipment that is shown on the process flowsheet. The students are shown aerial views of chemical plants and refinery layouts. Layouts in the department of model units are discussed. A general discussion of how to go about selecting a plant site on the basis of tangible and intangible items takes place before students begin this progress report.

PROGRESS REPORT 4—

Equipment Specification Details

The students submit detailed specifications for

each major piece of equipment shown on the flowsheet as if the specifications were being sent to equipment manufacturers for bids. The students survey equipment manufacturing catalogs and list three manufacturing companies that they would like to have bid on the various classes of equipment such as exchangers, pumps, etc. They also select three overall contractors from the literature reviews that they would prefer to build the plant (of course, without ever actually contacting any of these companies). A sample calculation of the size, etc., of each general type of equipment is required, such as, that of an exchanger, a fractionating tower, etc.

PROGRESS REPORT 5—

Instrumentation Flowsheet, Detailed Reactor Design

A proposed instrumentation flowsheet for the equipment shown on the process flowsheet is required. A detailed drawing of one major piece

Students are required to consider the instrumentation and practical application of economics by having to make an economic appraisal.

of equipment, generally a reactor which most plants will have, is required.

PROGRESS REPORT 6—

Economic Appraisal

An economic evaluation of the proposed plant showing the payout on a net profit and cash flow basis at assumed rates of 80, 100 and 120% of design capacity is required.

FINAL REPORT

The final report must be typed and assembled (including a cover letter) as if it were being submitted to the Board of Directors of a company for their consideration as a capital investment.

This course is required of all chemical engineering students that have completed or are enrolled in all their basic chemical engineering courses. Students that enter our graduate school who have not had a comparable course in plant design are highly encouraged to take this course as an elective and all foreign students are especially urged to take the course. Foreign stu-

dents from the same country are prohibited from working together in the same group in design to facilitate their learning to communicate in the English language.

The students are encouraged to take pride in the reports they submit. It is not difficult to get their cooperation, perhaps, because they are influenced by the knowledge that their report is kept in the files in the department indefinitely, and may be reviewed by students succeeding them. Each class that follows is encouraged to improve upon former students reports. No plants proposed for design ever have the same specifications as a previous report. They will generally be different in feed, product quality and annual capacity along with other variations. The prices on equipment, utilities, etc., are generally in keeping with inflation, and the size of plants in general have continuously shown a general increase in size over a twelve year period. There have been about 30 to 50 different varieties or types of plants theoretically built and evaluated on paper. These range from inorganic chemicals, such as caustic, chlorine, nitric acid and sulfuric acid, to the various types of alkylates, esters, organic acids, isoparaffins, cumene, paraxylene, etc. In general, the plants show cash flow payouts varying from about 3 to 10 years, depending on the size, type products, and feedstocks selected, when using current market prices for raw materials and product sales prices known to be realistic prices;—that companies are actually paying and receiving for the materials involved.

The use of progress reports was selected by the instructor because inexperienced students and engineers make many mistakes that would carry all the way through a design unless a careful progress check is made by an experienced engineer. By a system of checks by an experienced engineer, the big mistakes can easily be detected and the progress report returned to the group for correction. Progress report 3 has been placed between 2 and 4 to allow the instructor time to review the process flowsheet, the students are assigned the site selection and Plot Plan as a progress report. By this time the process flowsheet has been corrected and approved for the students to write out detailed specifications for all the major equipment. Since detailed specifications will be vital to the cost estimates, these need approval of the instructor. To allow him time for this, the students are asked to specify the instrumentation flowsheet and detailed reactor design in order to give them training in this aspect of communication. Any mistakes in progress reports 3 and 5 will not have any bearing on the economic appraisal performed in progress report 6. Pictures, scale model plants, and layouts of other plants on paper are used as aids in presenting data on how to complete progress reports 3 and 5, in particular.□



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EXPANSION AND CONTRACTION LOSSES IN FLUID FLOW

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Ann Arbor, Michigan 48104

IT IS GENERALLY AGREED that engineering students need experience in analysis of practical problems. A situation that may be of interest to engineering educators arose when the supposedly simple problem of calculating expansion and contraction losses was encountered in a study of coolant flow through the core of a nuclear reactor. It was thought at first that one merely had to go to standard texts or handbooks to obtain the necessary information, but that proved to be not completely satisfactory, as is to be shown.

In long pipelines, skin friction losses usually predominate so that estimates of minor losses due to expansions or contractions in diameter need not be very precise. In heat exchangers with large headers and relatively small tubes and in some nuclear reactor core configurations, however, it is the expansion and contraction losses which are great and must be determined fairly accurately. In most treatments of the subject expansion losses are considered first. Referring to Fig. 1A, the mechanical energy balance is written between points 1 and 2 as

$$\frac{P_1}{\rho} + \frac{u_1^2}{2} = \frac{P_2}{\rho} + \frac{u_2^2}{2} + F_e \quad (1)$$

where P is pressure, ρ is density, u is the average velocity, and F_e is the expansion loss (friction).

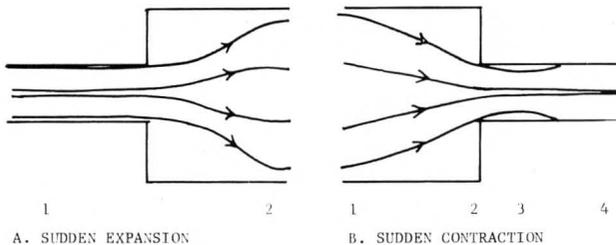


FIGURE 1.



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Next the momentum balance is applied between the same points with the pressure just inside the expanded section being the same as the pressure inside the smaller section so that

$$P_1 A_1 + P_1 (A_2 - A_1) - P_2 A_2 = u_1 A_1 (u_2 - u_1) \quad (2)$$

The pressure difference, $P_1 - P_2$, may be eliminated between Eqns. (1) and (2) to give the familiar Borda-Carnot relation,

$$F_e = \frac{(u_1 - u_2)^2}{2} = \frac{u_1^2}{2} (1 - A_1/A_2)^2 \quad (3)$$

where the continuity equation $u_1 A_1 = u_2 A_2$, has been used. This relation was studied experimentally by Schutt [8] and later by Kays [2] and shown to be excellent for turbulent flow at Reynolds Numbers of the order of 10,000 or more in the smaller section so that velocities are fairly uniform across the upstream and downstream cross-sections. For laminar flow the losses are somewhat less, but that was not of interest in the reactor problem at hand.

Contraction losses posed a different problem, for not one book showed a method of applying overall momentum and energy balances to predict these, probably because this case is not so simple as with expansion. In the usual treatment of the subject contraction losses are calculated by the expression,

$$F_e = \frac{K_c u_2^2}{2} \quad (4)$$

where reference is to Fig. 1B and K_c is a factor given by an empirical graph or equation. Values of K_c differ by as much as 50% between various authors and this was not acceptable for the nuclear reactor calculations. Figure 2 presents several suggested curves and many others were examined which gave the same values as one of those shown. Others, such as Bennett and Myers [1], give contraction and expansion losses in terms of equivalent length of straight pipe which is much too approximate for the desired results here.

The curve of Streeter [9] is based on century-old data, for he tabulated a contraction coefficient (area of vena contracta at 3 divided by the area at 2 or 4) which was measured by Weisbach [11]

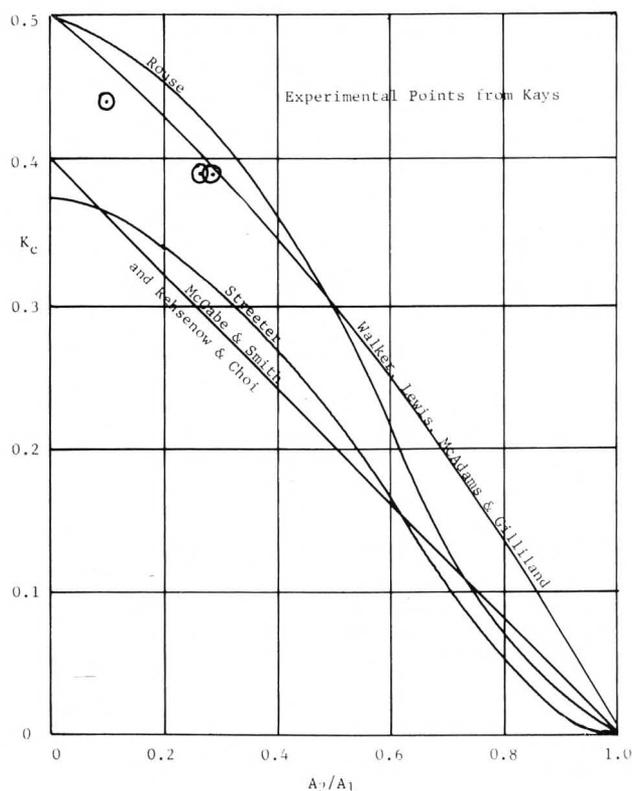


FIGURE 2.
Contraction Coefficient As Function Of Areas

The supposedly simple problem of calculating expansion and contraction losses was encountered in a study of coolant flow through the core of a nuclear reactor.

over a century ago, and inserted it into $K_c = (1/C_c - 1)^2$. However, Streeter also says, "The loss at the entrance to a pipeline from a reservoir is usually taken as $0.5 u_2^2/2$, if the opening is square-edged." This is obviously somewhat different from a value of $0.376 u_2^2/2$ based on Weisbach's data at $A_2/A_1 \approx 0$. Walker, Lewis, McAdams and Gilliland [10] referred to some early limited experimental data that could be represented by $K_c = 1.5(1 - A_2/A_1)/(3 - A_2/A_1)$ and it will be seen that this is good for mid-range values of A_2/A_1 , but poor at higher and lower values. McCabe and Smith [5] and Rohsenow and Choi [6] took an equation, $K_c = 0.4(1 - A_2/A_1)$, which Kays [2] developed for infinite Reynolds Number and this is much less than the preceding formulation. Rouse [7] utilized two-dimensional irrotational flow analysis to obtain his results. The points on Fig. 2 are the carefully measured values of Kays [2] for both single and multiple tube arrangements for Reynolds Numbers of the order of 20,000. It is seen that none of the correlations fits the data with high precision over all ranges of the area ratio.

In view of the similarity in flows through a sharp-edged orifice and through a sudden contraction, it seemed reasonable to apply known orifice behavior to the contraction problem. An experimental study [4] of the pressures on the upstream face of a sharp-edged orifice plate showed that the average pressure on the plate differs slightly from the upstream pressure, so that the net pressure acting on the fluid between the upstream and the vena contracta can be given as $m A_2 (P_1 - P_3)$. The factor m is unity for the ideal case of a perfectly uniform pressure of P_1 over the upstream orifice plate face, but differs a little from unity in actual cases. Applying the mechanical energy and momentum balances between the upstream and the vena contracta with the assumption of no losses [4] before the vena contracta gives by using $u_1 A_1 = u_2 A_2 = u_3 A_3$, where A_3 is the cross-sectional area

of the vena contracta,

$$u_2 = \frac{m}{\sqrt{1-mA_2/A_1}} \sqrt{\frac{2(P_1 - P_3)}{\rho}} \quad (5)$$

The usual orifice equation with the approach velocity correction is written

$$u_2 = c \sqrt{\frac{2(P_1 - P_3)}{\rho [1 - (A_2/A_1)^2]}} \quad (6)$$

Comparison of (5) and (6) yields

$$c = \frac{m}{2} \sqrt{\frac{1 - (A_2/A_1)^2}{1 - mA_2/A_1}} \quad (7)$$

Lamb [3] reported that Kirchoff and Rayleigh had studied ideal flow in two dimensions through an orifice in a large chamber by complex variable transformation and found $C = \pi/(\pi + 2) = .6110$. The ASME Fluid Meters Report [12] showed that for a wide range of D_2/D_1 and Reynolds Numbers in turbulent flow in actual orifices C varied from 0.590 to 0.615. Thus, a round value of 0.6 may be taken for either an orifice or a sudden contraction so that Eqn. (7) becomes

$$\frac{1 - mA_2/A_1}{1 - (A_2/A_1)^2} = \left(\frac{m}{1.2}\right)^2 \quad (8)$$

and m is seen to be a function only of the area ratio. In terms of m between points 1 and 3 in Fig. 1B the momentum balance is

$$u_1 \rho A_1 (u_3 - u_1) = mA_2 (P_1 - P_3) \quad (9)$$

while the mechanical energy balance for frictionless flow as assumed in Reference [4], is

$$\frac{P_1}{\rho} + \frac{u_1^2}{2} = \frac{P_3}{\rho} + \frac{u_3^2}{2} \quad (10)$$

If now $P_1 - P_3$ is eliminated between (9) and (10) instead of u_3 , the vena contracta velocity, as was done to get Eqn. (5), the result is

$$u_3 = u_2 (2/m - A_2/A_1) \quad (11)$$

Between points 3 and 4 the momentum balance is

$$u_1 A_1 \rho (u_4 - u_3) = (P_3 - P_4) A_2 \quad (12)$$

and the mechanical energy balance is

$$\frac{P_3}{\rho} + \frac{u_3^2}{2} = \frac{P_4}{\rho} + \frac{u_4^2}{2} + F_c \quad (13)$$

Eliminating $P_3 - P_4$ between (12) and (13),

noting that $u_2 = u_4$ and using (11) gives

$$F_c = (2/m - A_2/A_1 - 1)^2 \frac{u_2^2}{2} \quad (14)$$

Comparison of (14) and (4) shows that

$$K_c = (2/m - A_2/A_1 - 1)^2 \quad (15)$$

where m is the function of A_2/A_1 in (8). It is seen that fixing A_2/A_1 determines K_c . This has been done and the results compared with Kay's experimental data in Fig. 3. The agreement is within the error of the measurements themselves.

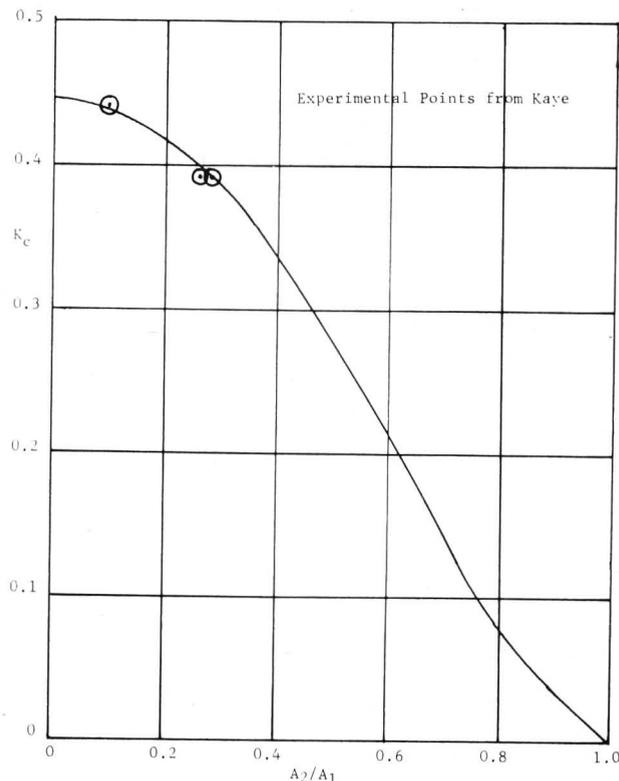


FIGURE 3.
Contraction Coefficient From Equations (8) and (15)

One concludes, therefore, that a sudden contraction is similar to a sharp-edged orifice up to the vena contracta and that the analysis by the overall mechanical energy and momentum balances along with known orifice behavior is the correct approach to this problem. Losses due to sudden contraction may, thus, be calculated with excellent precision by use of Eqns. (4), (8), and (15) or the equivalent Fig. 3.

The foregoing development assumed constant density, as for a liquid. The application can also be made to a gas if the pressure drop is not too great so that an average density may be used, since this was shown to be true in the orifice study [4]. □

(Continued on page 148)

CACHE COMPUTER PROBLEMS



CHEMICAL ENGINEERING EDUCATION, in cooperation with the CACHE (Computer Aides to Chemical Engineering) committee, is initiating the publication of proven computer-based homework problems as a regular feature of this journal.

Problems submitted for publication should be documented according to the published "Standards for CACHE Computer Programs" (September 1971). That document is available now through the CACHE representative in your department or from the CACHE Computer Problems Editor. Because of space limitations, problems should normally be limited to twelve pages total; either typed double-spaced or actual computer listings. A problem exceeding this limit will be considered. For such a problem

the article will have to be extracted from the complete problem description. The exact procedure to distribute the total documentation is evolving and may involve distribution at the cost of reproduction by the author.

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THE CHEMICAL ENGINEERING PROFESSION AND COOPERATIVE EDUCATION

W. H. TUCKER
Tri-State College
Angola, Ind. 46703

COOPERATIVE EDUCATION, STARTING with the program at the University of Cincinnati in 1906, had a linear growth in the United States during its first 40 years. Recently, the expansion rate has become more nearly exponential. For example, the number of United States educational institutions offering the co-op program has increased from 55 to 369 from 1963 to 1973. While part of this growth has resulted from activity in the two-year colleges, it is nevertheless a fact that cooperative education is meeting the present need for relevance in education. Students are more than ever wanting to relate their academic training to life in the real world. In chemical engineering, 55 institutions out of United States total of 110 now offer cooperative education—mostly on an optional basis. [1, 2] From these references, we can estimate that over 15% of United States chemical engineering students are pursuing cooperative education, usually with five years to the B.S. degree. A parallel growth in engineering co-op education has occurred in Canada, and in Britain, the growth has been dramatic.

Reference 1 gives a definition of the cooperative program as follows:

Cooperative education may be defined as the integration of classroom theory with practical experience under which students have specific periods of attendance at the college and specific periods of employment.

The following factors should be adhered to as closely as possible:

- Where possible, the student's work should be closely related to his field of study and individual interest within the field.
- The employment must be considered to be a regular, continuing and essential element in the educational process, and some minimum amount of employment and minimum standard of per-

formance must be included in the requirement for the degree or certificate presented by the school.

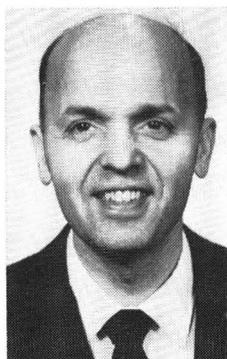
- The working experience will ideally increase in difficulty and responsibility as the student progresses through the academic curriculum and, in general, shall closely parallel his progress through the academic phases.

OPERATING THE CO-OP PLAN

WHILE THERE IS CONSIDERABLE diversity in the scheduling of work periods in industry, a typical plan would be to place the student in industry at the end of his freshman year after he has established an academic record. Over the next four years, the student would be on some alternating schedule that would give him in the neighborhood of 20 months of industrial work in his B.S. program. The scheduling will vary between semester and quarter arrangements in the colleges. A given company will thus be faced with a confusing array of student schedules. Formerly, this was a serious matter when co-op students had to be considered as pairs, each pair filling a given job on a continuous basis. The recent trend has been toward giving each student a unique experience with an emphasis on project work. Thus, there is less routine work except where it is desirable in the student's development. Companies tend now to employ students as singles, whatever their schedules.

Most students come to a college-based program, where the college places a student in a situation in which neither he nor the company is

The author appeals to the ChE profession to take a greater interest in the co-op movement, to give the student a more professional experience.



W. Henry Tucker received the B.S. degree from the University of Virginia, and the S.M. and Sc.D. from M.I.T. '47. He has had industrial experience with several companies and was in charge of the chemical engineering cooperative education program while he was on the faculty at Purdue University. In 1969 he received the AIChE Winston Churchill Travelling Fellowship, which included a study of the cooperative education program in Britain. He presently is in charge of the Chemical Engineering Curriculum at Tri-State College, Angola, Indiana, and has absorption refrigeration as his primary engineering interest.

obligated as far as permanent employment is concerned. The industry-based program, in which the company selects one of its employees for a co-op program, is sometimes found. A hybrid arrangement is helpful in this period of declining engineering enrollments. A given company can take the initiative to recruit students in high school for a college-based program, providing that their freshman year in college is academically good. One can also emphasize minority groups who can be encouraged by the co-op idea.

Colleges differ in the matter of placing a student with one company for all of the work periods or with diversified employers. There are advantages for each arrangement in the breadth-depth plane of experience. A single company can certainly provide more responsibility in the latter work periods. It is probably a safe generalization to conclude that a large company, say one with more than 25 engineers, can provide the needed variety for a given student. If a company is small, the student should work with more than one during his program for a comparable variety. Sometimes, a company will shift a student to several locations to give the needed experiences.

As to salary, a co-op student in engineering would be expected to earn in the neighborhood of \$12,000 in 20 months of experience. Financially, though, it might be more attractive to graduate in four years on a regular program and have a year of higher salary. The co-op, however, does minimize his debts while in college. But salary alone

will not justify the program; the co-op student must have a desire for engineering experience while in college to the same degree as his desire for money.

This article continually refers to co-op employment by companies. It should be pointed out here that the Federal Government is a recent strong entry into the field, though state and local governments are slow to follow suit. The Federal scene is described in a recent article [3].

THREE-WAY CO-OP COORDINATION

THE COORDINATION which must take place between the student, the college coordinator and the company contact official is the key factor in the successful operation of any program. It is still too often the case that academics or employers take the program casually, assuming that the creation of a job is all that is necessary for some osmotic process to take place which will enrich the student's academic experience. It turns out that the co-op program must be *managed*. If a college coordinator does his job properly, his ac-

We estimate that over 15% of U.S. ChE students are pursuing co-op education, usually with five years to the B.S. degrees.

tivities are surprisingly complex. Charles Seaverns has developed a meaningful list of 14 functions to be fulfilled by the college coordinator [4], making him a "placement specialist, vocational counselor, salesman, teacher, administrator, educational recruiter, trouble-shooter, mediator, and referral agent."

The recent *Handbook of Cooperative Education* [5] amplifies many areas in the academic area of coordination. Except in company files, there is a distinct lack of material available to speak to the coordination problems faced by the industrial people where the real action is. To help fill this gap, the author has prepared the publication, *Effective Supervision of Engineering Cooperative Education Programs* [6]. The "company contact official" is the key man in the company organization. He must keep in contact with the student and with his progress by also working through the student's immediate supervisor.

. . . it is a fact that co-op education is meeting the present need for relevance in education.

Dr. J. W. Morris has commented on his organization at a DuPont plant [7]. He describes a high-level Co-op Advisory Committee to set co-op policy. He also mentions the success he has had with extra curricula supervision of co-op students by a young employee who himself had earlier been a co-op student employee. Companies in general find it difficult to sustain effective coordination of a co-op program, since it is likely that the contact officer will spend only a couple of years, enroute to other personnel assignments. The college coordinator finds more permanence in his job.

On the industrial scene, the company contact official will certainly be concerned with three areas: orientation, actual work experience, and evaluation. Proper **orientation** should be spread over all of the work periods rather than to be limited to the first day of the initial work period. Orientation does not just cover the physical plant, but also the organization, procedures and policies of the organization. For an effective **work experience**, the projects to be handled by the co-op student should be pre-planned. The college coordinator is interested in the educational objectives of the work, while the company wants to select experiences which are reasonable within the time frame and the ability of the student. Many companies do not pre-plan, but engage in a flurry of activity when the student shows up for work. Finally, the **evaluation** of the student's work is many times poorly done if one is to accept the heavy student criticism of his evaluation. The company contact officer and the student's supervisors should get together with the student with detailed and meaningful comments on his performance. A summary of this evaluation is then passed on to the college coordinator. One aspect of the evaluation step is to begin the pre-planning for the next work period.

The college coordinator must visit the student and his supervisors for effective coordination. Unfortunately, usually limited travel budgets allow visits only once in two years or more, and this is inadequate. The background of the college coordinator is important, too. In the United States, one usually finds a coordination staff which is

completely removed from the college engineering departments. A few colleges use chemical engineering faculty as coordinators for chemical engineers; Purdue University is such an example. But, for the most part, college coordination has developed its own administrative organization. The British represent the opposite extreme. Coordination there is managed by the chemical engineering department chairman. He selects a coordinator in his department, and the visitations are handled by the entire departmental faculty with usually two visits to the student site each work period.

The company contact official should find occasion to visit the college campus. Purdue University has Co-op Days each spring, at which time, company people come in to select their students. Also, the company contact officer might be a member of a policy committee at the college. Professor J. G. Wohlford has described the Co-op Advisory Council in operation at Georgia Tech [6].

CO-OP ORGANIZATIONS

SEVERAL ORGANIZATIONS are presently looking out for the welfare of cooperative education:

- The Cooperative Education Association is the umbrella organization for all of cooperative education [8]. It publishes the *Journal of Cooperative Education*. It encourages regional training centers for developing new coordinators.

- The ASEE maintains the Cooperative Education Division, which is specifically concerned with engineering programs [9].

- A policy organization concerned with establishing new programs and obtaining Federal assistance is the National Commission for Cooperative Education [10]. Federal financial assistance to new or developing programs is available through the 1968 amendments to the Higher Education Act of 1965. Yearly assistance of about two million dollars is presently granted.

ACCREDITATION OF PROGRAMS

Currently, there is a cooperative effort between the Cooperative Education Division, ASEE, and the Engineering Council for Professional Development (ECPD) to develop criteria for the accreditation of engineering and engineering technology co-op programs. A summary of these criteria is given by Professor J. G. Wohlford [11]. Accreditation of co-op programs seems a certainty.

NOT UNRELATED to accreditation of programs by ECPD is the granting of academic credit for work experiences, except that this is an internal matter in each college. Many college faculty members are extremely reluctant to allow credit to be granted for work done entirely away from campus. Nevertheless, the granting of academic credit is growing; and thus, the academic community is asserting that a work experience can have academic value. John H. Sherrill indicates that, as of 1971, about 46% of the co-op programs were granting credit [12] as compared with 21% in 1969. Additional institutions grant meaningless credit; credit that cannot be used to substitute for other courses in the curriculum. The few institutions that require the co-op program for all engineering students do not need to grant credit. There is an extreme variation of amount of credit given and the criteria used to decide on the academic value of the work experience. Tri-State College grants four credits but only after the completion of several effective work periods. In one case, credit was given back at the university for a series of seminars in which the students and the coordinator took up topics of relevance to the program [13].

The trend is for more graduate programs with the co-op flavor. Some of these are summarized in reference [5], page 70. One can imagine that particularly in an urban environment, there can be a great variety of programs, as a student splits his day between work and classroom. It is necessary to judge the relevance of the work experience to

Students are more than ever wanting to relate their academic training to life in the real world.

determine whether it is truly a cooperative education program. One specific experiment involving the major professor in the industrial program along with the students has been reported [14]. The experiences of a student in a graduate level co-op program are described in a recent article by King [15]. His Ph.D. program was an extension of his B.S. experience at the same company.

DEVELOPING BROADER PROFESSIONALISM

The excellent co-op programs in Britain and

Canada suggest the idea of exchange programs. These could be arranged through college coordinators but the extra effort and paper work are considerable. A United States company can arrange for a co-op student to spend his last work period in any part of the world at considerable advantage to the company and to the student (the use of a foreign language in a working community). The occasions in which exchanges have been tried have not been publicized in the co-op literature.

A different kind of international emphasis is possible—that of students from the developing countries coming to the United States for their work experience, as well as for their college education. The American company would be willing to invest in a foreign student program when the student would indicate his intention to return home and work as a permanent employee of the American affiliate [6].

There are many lost opportunities to develop the student professionally while he is on the job. He could be made more aware of the ethics of his profession as well as the social and political implications of engineering. As a first step, one could involve him in the program and committee activities of the Local Section of AIChE. In the book, "*The Student in Society*" [16], two emphases are found: the student is shown how to settle into a new community with the minimum of hardship, and he is encouraged to use the community as a learning laboratory to develop sociological and political concepts.

SUMMARY COMMENTS

This article is an appeal for the chemical engineering profession to take a greater interest in the co-op movement, to give the student a more professional experience. The AIChE Educational Projects Committee sponsored a cooperative education symposium at the February, 1972 Dallas meeting. Subsequently, it encouraged the preparation of the manual on co-op supervision [6], but the talking is all being done by the academic people. AIChE industrialists related to co-op supervision should organize to discuss ways in which the co-op experience could be an involvement in professionalism so that the latent possibilities of the program could be realized with a larger percentage of the students. At any rate, the fact that 15% of our students are on this program should alert our profession to provide for its special needs. □

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ChE book reviews

Process Synthesis, D. F. Rudd, G. J. Powers, and J. Siirola, Prentice-Hall, Inc., (1973), 320 pp.

Reviewed by

C. M. Thatcher, University of Arkansas

A good textbook must effectively serve a worthwhile objective; and, even then, publication is fully justified only if either the objective itself or the treatment thereof is sufficiently unique. By these standards, Rudd, Powers, and Siirola have written a text which is not merely good, but excellent.

The authors' stated objective is to approach process development via a careful interlacing of synthesis and analysis, and "to present the material in a coherent and attractive form suitable for the students' first exposure to an engineering course". The fact that the presentation reflects the results of recent research in process synthesis makes this objective as timely as it is worthwhile.

As for uniqueness, the distinction between "design" and "synthesis" is subtle, but it is fully and effectively exploited in this text. The major concern is with those qualitative decisions which precede detailed design calculations. Process design texts, in contrast, commonly emphasize the latter and may not even mention the many prior decisions which underlie the "given" information

which they present as a starting point for quantitative calculations.

The detailed and well-organized attention given the criteria for selecting a particular process scheme from among a number of possible alternatives is equally unique. Process design texts may consider various alternatives for a specific case at hand; but Rudd, et al, identify with commendable thoroughness and clarity those *general* criteria which are applicable to *all* such cases.

The major thrust of the book is embodied in separate chapters devoted to Reaction-Path Synthesis, Material Balancing and Species Allocation, Separation Technology, Separation Task Selection, and Task Integration (energy considerations, primarily). Each of these chapters develops an appropriate strategy for identifying those processing schemes which are likely to be feasible and then making a specific selection from among the several prospective alternatives.

An introductory, overall view provides some historical perspective and sets the stage for the successive consideration of the foregoing topics. The two final chapters then examine two specific applications in detail: fresh water by freezing, and detergents from petroleum.

Does the book effectively serve the authors' objective? As far as scope, thoroughness, organi-

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zation, and clarity of presentation are concerned, the answer is an unqualified "Yes". The extent to which the text is, in fact, "suitable for the students' first exposure to an engineering course" necessarily depends on how it is used, however.

The authors view their approach as "a replacement for the traditional course in material and energy balancing", but admit that some traditional topics must then be treated in subsequent courses. The synthesis-oriented approach, they report, produces students who can screen reaction sequences, "make a pretty good material balance", allocate materials, select separation phenomena, and use energy balances, all with due regard for process economics, as they synthesize complete process flow sheets.

Even so, the very uniqueness of the synthesis approach makes it difficult to use this text as the basis for a conventional beginning course in stoichiometry, etc. But the book should very definitely be of interest to the instructor who is willing to accept the synthesis-oriented philosophy along with or in place of the traditional first-course approach.

As an alternative to first-course use, it is recommended that the book be seriously considered

either as a text or as a key reference source for process design studies at the senior level. Decisions of the type treated by Rudd, et al, are a very real part of chemical engineering practice, and the student should be prepared to make them. *Process Synthesis* appears to be an excellent vehicle for such preparation. □

NOTICE TO DEPARTMENT CHAIRMEN

The Fall 1974 issue of CEE is a special issue on graduate education that will be distributed to ChE Chemical Engineering seniors interested in graduate school

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NEBRASKA'S INTEGRATED PROCESS LAB: Reilly, Timm, Eakman

(Continued from page 118.)

tice in independent thinking and their added self-confidence have been helpful to them in industry.

Table II. REPORT SUBJECTS

First Semester

- Analogous commercial processes—Esterification mechanisms
- Possible rate equations—Proposed kinetics experimental design
- Interim kinetics data
- Final kinetics data and model evaluation

Second Semester

- Batch, tubular, and CSTR sizing
- Reactor costing
- Estimated boiling points
- Estimated vapor pressure curves
- Estimated vapor-liquid or liquid-liquid equilibria
- Final report—Plant design, product cost, and location

The more perceptive students quickly recognize the link between theory and experiments, and they use theory successfully to design experiments. The lesson is later solidified, since experimental data must be extrapolated with theory to obtain proper design.

Eventually the usefulness of proper experimental design becomes apparent to nearly everyone. Unfortunately for many of the students, this awareness often does not come early or easily. If we were primarily interested in good results during this laboratory, we would take a more direct hand in helping students set up their experiments. Since, however, we view the laboratory mainly as a learning tool, we allow quite a bit of slipping and sliding before stepping in.

One of the unexpected results was that three-man groups were over any extended period more unstable than groups of either two or four members. Usually one or occasionally two of the three did not carry a fair share of the load. This of course led to hard feelings, even though we pointed out to the aggrieved parties that they probably learned more that way. The problem was solved by going to two-man groups. Only a very exceptional person has the temerity to leave the whole load on his partner. Conversely, the dominant partner, if one emerges, realizes that civility

enlists more cooperation than alternate modes of behavior.

POSTSCRIPT

TO SOME EXTENT this approach has some flavor of reinventing the wheel, since we learned long after undertaking it that the late Professor Vilbrant at VPI had trod a similar path a number of years ago. However, the development of this sequence has educated us during the past five years perhaps more than any of our students. Our appreciation goes to those students who have volunteered advice, some of it perhaps not so well received at the time, that indicated which of our many changes were successful and which were not. No course of this type can ever stand still. We, therefore, hope that our students in the future will be equally free with their help. □

EXPANSION AND CONTRACTION

LOSSES: Martin

(Continued from page 140.)

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SEEING ENTROPY - The Incomplete Thermodynamics of the Maxwell Demon Bottle

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MOST OF US have heard of Maxwell's Demon but entirely too few know of the Maxwell Demon Bottle [1, 2, 3]. This fact, although forgivable is entirely unfortunate because the bottle not only has sealed within it a Maxwell Demon—but also contains means for elucidating in a visible and even amusing fashion many of the fundamental concepts of thermodynamics.

What is the Maxwell Demon Bottle?

The Maxwell Demon Bottle (hereinafter called MDB) is the simple device shown in Figure 1 which consists of a long necked, sealed, flask containing a number (usually 10) of colored cork or rubber spheres. As usually constructed, 5 of these spheres are black and 5 are white. When the flask is held in a neck down position the spheres fall into the neck in a columnar array.

But what does this have to do with thermodynamics?

Well an important part of thermodynamics is concerned with the fact that Nature is not at all even-handed in the direction in which she moves phenomena. For example, apples fall from branches above to the ground below, and never move spontaneously in the opposite direction. A steel ingot always cools when taken from the furnace. Humpty-Dumpty never gets put together again. We grow older.

Nature's processes abound in irreversibility. They move easily in one direction and not at all or only with great effort in the reverse.

Why? Why, for example, is it easier to move from cream and coffee—separate entities, to—cream and coffee—mixture, than in the reverse direction? The MDB evolved from an old demonstration aimed at answering this very question; a demonstration to illustrate that *statistics*, rather than design, lies behind the irreversibility of a mixing process [4].

The demonstration is shown in Figure 1, 2 and 3. Starting with the flask in the neck down position and an array of 5 black spheres surmounted by 5 white spheres, the flask is tilted to allow the neck contents to run into the body. When the flask is reinverted the spheres again run into the neck but usually not in the initial array. The reason is, of course, that there are 252 possible arrays or permutations of 5 black and 5 white balls ($10!/5!5!$) and once the initial

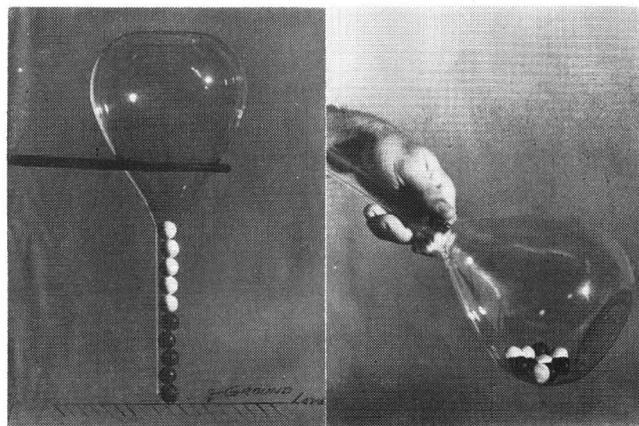


Figure 1. The "Maxwell Demon Bottle" in its initial state.

Figure 2. Tilting the bottle disarranges the initial state . . .

array is destroyed, the likelihood of reforming that array is very small.

In mixing solutions we are intermingling not 10 particles but numbers of particles in the order of 10^{23} . Therefore, the number of possible permutations of these particles is astronomically large and the likelihood of regaining the original array by chance is so small as to be considered impossible.

Thus, it is seen that mixing processes owe their irreversibility to statistics—that is, to the negligible likelihood that a unique array of an astronomically large number of particles, once disturbed, can be regained by chance selection—rather than to forces or to design.



Dr. M. V. Sussman is peripathetic professor of chemical engineering at Tufts University and the man who first bottled the Maxwell Demon (U.S. Patent No. 3,289,321). He is also the author of that recently published (Addison Wesley) thermodynamics textbook, with a perpetual motion machine (courtesy of M. Escher) on its dust jacket. Among other singular activities are works on continuous gas chromatography and "muscle" turbines. His thermodynamic ruminations have appeared in this journal previously ("Approaches to Statistical Thermodynamics," Chem. Eng. Ed., p. 113-118, Summer 1968).

MORE THERMODYNAMICS: ASSIGNING AN ENERGY TO THE MDB

But the MDB contains more thermodynamics than this. For example, an *energy* can be assigned to the MDB by the following stratagem. Assume that the black spheres each have unit mass, while the white spheres are merely massless spacers. If the bottle is supported in a neck down position as in Figure 3 with the top of the neck resting at table level, we can assign an energy value to each ball position corresponding to its elevation above the ground or reference level. Thus, we will assign an energy of zero units to the lowest position in the neck of the bottle and

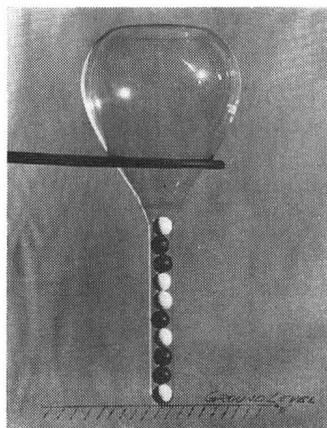


Figure 3. Re-inverting the bottle usually does not restore it.

energies of 1, 2, 3, 4, etc., energy units to each subsequent level. For example, the energy of the array in Figure 1 is

$$E_{k1} = 0+1+2+3+4 = 10 \text{ energy units}$$

whereas the energy of the array in Figure 3 is

$$E_{k3} = 0+4+5+7+8 = 24 \text{ energy units,}$$

and in general

$$E_k = \sum_{i=1}^M n_i \epsilon_i \quad (1)$$

where n_i is the number of black balls in the "i"th level and may be either 0 or 1, and ϵ_i is the energy magnitude of the "i"th level, which may have any integral value between 0 and M, the maximum energy level that can be reached. Now engaging in a flight of fancy nomenclature, let us call each array a "state." We have already pointed out that with 5 white and 5 black balls the system can have 252 "states." The states can have energies ranging from 10 units (state 0,1,2,3,4) to 35 units (state 5,6,7,8,9). The states are specified by the 5 ϵ_i 's of the black balls. One would therefore *expect* that on the average the energy of the MDB will be

$$\langle E \rangle = \sum_{k=1}^{252} P_k E_k \quad (2)$$

where P_k is the probability of state "k", or the chances of getting a particular permutation of black and white balls;

E_k is the energy magnitude of that state as given by equation (1); and

$\langle E \rangle$ is the expected energy, or the probable average of future energies, of the MDB, taking into consideration all possible permutations or "states."

If we now apply elementary calculus to Equation (2) we find that the differential of the expected energy of the MDB equals

$$d\langle E \rangle = \sum_k \epsilon_k dp_k + \sum_k p_k d\epsilon_k \quad (3)$$

which says that there are 2 ways of changing the energy $\langle E \rangle$:

(I) by changing the p_i 's while holding ϵ_i 's constant: and

(II) by changing the ϵ_i 's at constant P_i 's

Equation (3) is intriguingly similar to the equation in classical thermodynamics for the differential of energy in a simple system:

$$dU = dQ_{REV} - dW_{REV} \quad (4)$$

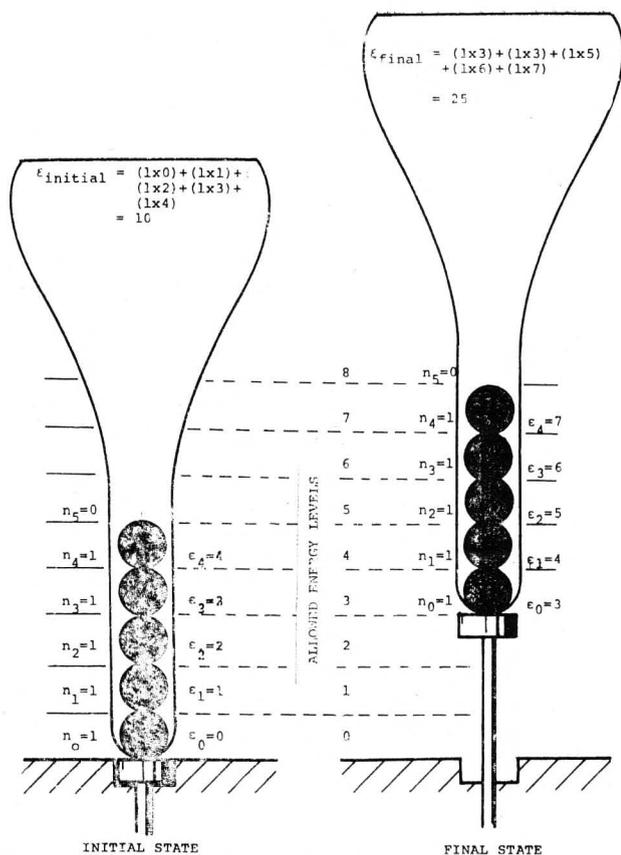


Figure 4. The energy of the "Bottle" may be increased by a Reversible Work Effect.

which also says that the energy can be varied in two ways:

- (I) by a heat effect, dQ_{REV} ; and
- (II) by a work effect, $-dW_{REV}$.

On the strength of the analogy between equations (3) and (4) we will call

$$\sum_x \epsilon_x dp_x \equiv dq_{REV} \quad (5)$$

or the bottle analog of heat

$$\sum_x p_x d\epsilon_x \equiv -dw_{REV} \quad (6)$$

or the bottle analog of work and,

$\langle E \rangle \equiv U$ or the bottle analog of *internal energy*.

(WORK AND HEAT EFFECT)

A WORK EFFECT OCCURS when the p_x are held constant and the ϵ_x are varied. This is easily accomplished by changing the elevation of the bottle. If the bottle is raised, for example as in Fig. 4, the magnitude of each of the ϵ_x 's is increased without disturbing the n_x 's. Hence, the ϵ_x are changed without changing the p_x . In short, work is performed on the MDB system by a change of an external parameter, the elevation,

much like work is done on a gas by changing another external parameter, the volume.

Continuing the analogy, a heat effect, $\sum_x \epsilon_x dp_x$, is accomplished by changing the probability of a given state of black balls without changing the elevation. This may be done by adding or removing white balls from the bottle thereby changing the number of permutations and therefore the probability of a given permutation or state.

A profound difference between reversible work and heat becomes apparent when equal amounts of these forms of energy are added to a MDB. For example, the 2 black ball one white ball MDB of Fig. 5a has an expected energy of 2 units, (all arrangements are equally likely), which can be increased to 4 units either by raising the entire system one diameter (adding 2 units of work energy, 5b) or by adding 2 white balls (adding 2 units of heat energy, 5c).

Now although the 5b and 5c systems have the same store of expected energy, they differ in the *availability of that energy for doing work*. The 5b system can release 2 units of its energy as work by simply dropping to the 5a position, whereas the 5c system *cannot drop* and therefore *cannot* release energy as work (unless perhaps means are found to drain off excess white balls without reducing $\langle E \rangle$).

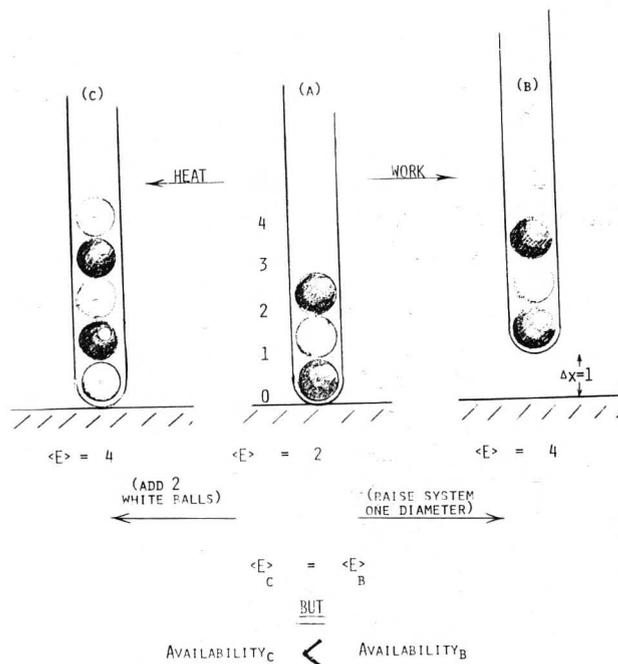


Figure 5. Changes produced by equal heat and work effects: Although (B) and (C) have equal interval energies, (B) can release work, whereas, (C) cannot, therefore (B) has more Available Energy.

The generalization of this observation is that if two systems store the same amount of energy, the more disordered of the two can do less work than the less disordered. I know no simpler illustration of this fundamental thermodynamic principle.

"SEEING" ENTROPY

LET US SUPPOSE that as suggested above, white balls, the massless spacers, can in some manner be added to the bottle at will, and starting from a system containing only 5 black balls, examine the effects of successive additions of white balls.

Nature's processes abound in irreversibility . . . they move easily in one direction and not at all or only with great effort in reverse.

With only 5 black balls (Figure 6a) the system has an energy of 10 units (0+1+2+3+4). On addition of 1 white ball (6b), the system may have any one of the 6 energies between 10 and 15 as the white ball occupies any of the 6 possible positions between ϵ^0 and ϵ^5 . For example, Figure 6b shows the system when it has an energy of 12 units. With 2 white balls added (6c), the energy of the system can take on values from 10 to 20 units and the balls can form:

$$\frac{7!}{5! 2!} = 21 \text{ states or permutations.}$$

Three white balls, (6d), make possible energies between 10 and 25 and allow:

$$\frac{7!}{5! 3!} = 56 \text{ states}$$

and as previously noted, 5 white balls allow energy states ranging from 10 to 35 units and permit 252 states.

In general n_w white balls added to a 5 black ball system will make possible energies ranging from 10 to $10+5n_w$ units with

$$\frac{(5+n_w)!}{5! n_w!} \text{ possible states.}$$

The introduction of white balls has two effects. It makes it possible for individual black balls to climb higher into the neck of the flask to higher energy levels making possible increased

values of ϵ_g ; and in addition it has the curious effect of introducing *indeterminacy* into the system, because each white ball increases the number of ways black balls and individual energy levels may be permuted.

The number of possible permutations of black balls in accessible energy levels is an intriguing characteristic of the MDB which we shall make the basis of a property here christened "Bottle Entropy," and defined as:

$$S' = k \ln w \quad (7)$$

Thus, S' is proportional, to the natural logarithm of the number of permutations, w (k is a constant). Clearly S' increases as we add white balls and increase the possible states of the system, and S' goes to 0 as the number of white balls goes to 0 and the permutations drop to unity.

EXTENSIVE NATURE OF "S"

LET US AGAIN CONSIDER an MDB containing only two black balls and one white ball. This system can exist in $3!/2!$ or 3 states, and if all these states have equal probability then,

$$S' = k \ln 3$$

The three states are shown as columns of B's and O's in Table 1a.

If we were now to place a second identical MDB alongside the first, that is, if we were to *double* our system, the entropy of the *doubled* system consisting of MDB_1 and MDB_2 would be

$$S_{1+2} = k \ln w_{1+2}$$

where w_{1+2} is the number of states available when 2 MDB's are considered simultaneously.

Now if bottle 1 were in state (0, 1) (Table 1b), bottle 2 could be in any of its three possible states. Similarly, if 1 were in state (0, 2) bottle 2 again could be in any of its three possible states. The magnitude of w_{1+2} is therefore found by combining every state of one bottle with all possible states of the other bottle. Or

$$w_{1+2} = w_1 \cdot w_2 = 3 \times 3 = 9$$

and $S_{1+2} = k \ln w_1 \cdot w_2$

$$= k \ln w_1 + k \ln w_2$$

or $S_{1+2} = S_1 + S_2 \quad (8)$

and $S \text{ (of } N \text{ identical MDB's)} = N(S_1) \quad (9)$

or S depends on the number of bottles comprising the system and therefore is an *extensive* property.

CONDITION (a)
THE POSSIBLE STATES OF A 2-BLACK, 1-WHITE BALL MDB

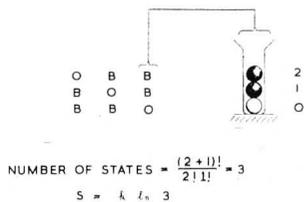


Table 1 (a)

CONDITION (b)
THE POSSIBLE STATES OF TWO MDB'S

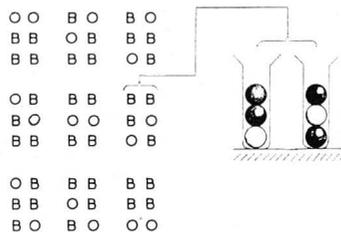


Table 1 (b)

CONDITION (c)
STATES OF TWO MDB'S HAVING DISTINGUISHABLE PARTICLES WHICH MIX

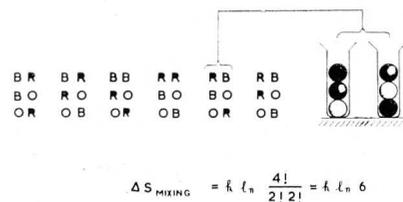


Table 1 (c)

THE ENTROPY OF MIXING

If, by some unspecified diffusion process, the black balls of bottle one can *interchange* positions with those of bottle 2, the entropy effect is that described in the previous paragraph because the black balls are all indistinguishable. If, however, the particles of bottle one are distinguishable from those in bottle 2, for example if 2 has red spheres and 1 has black spheres, (or if 2 has heavier spheres than 1), then there is a large and additional entropy increase because a large number of new 2-color states are created by the diffusional mixing. (Table 1c).

The total states in a system consisting of a 2 black sphere—one white sphere MDB, and a 2 red sphere—one white sphere MDB, is all the states of a two-bottle system, multiplied by the number of ways the 2 red and 2 black spheres can be interchanged or permuted in each of these double-bottle states. Now, each of the double bottle states can be permuted. $(2+2)!/2!2! = 6$ ways (Table 1 c, d)

Therefore $w_{r+b} = w_r \cdot w_b \cdot \frac{(n_r + n_b)!}{n_r! n_b!} = 3 \times 3 \times 6 = 54$ (10)

Consequently $S_{r+b} = k \ln w_r + k \ln w_b + k \ln w_{\text{mixing}}$

OR $S_{r+b} = S_r + S_b + \Delta S_{\text{mixing}}$ (11)

where $\Delta S_{\text{mixing}} = k \ln \frac{(n_r + n_b)!}{n_r! n_b!}$ (12)

When we deal with very large numbers of particles as for example in the preparation of solutions of liquids or gases, Stirling's Approximation for $\ln(n!)$ may be employed

$\ln(n!) = n \ln(n) - n$ (13)

in Equation (12) which transforms it to

$\Delta S_{\text{mixing}} = -nk \sum_i x_i \ln x_i$ (14)

where x_i is the fraction of particles that are of the "i" kind, and n is the total number of particles.

If in addition k is taken to be the Boltzmann constant or, R/\bar{N} , the gas constant divided by Avagardo's number, then nk becomes NR , the total number of moles multiplied by the gas constant. Equation (14) is then the classical expression for the entropy of mixing ideal solutions:

$\Delta S_{\text{mixing}} = -NR \sum_i x_i \ln x_i$ (15)

TABLE 1(d) ENTROPY AND ENERGY OF MIXING

POSSIBLE STATES AND ENERGIES OF TWO MDB'S
THE COLORED PARTICLES OF WHICH ARE DISTINGUISHABLE AND INTERCHANGE POSITIONS

e_i	1	2	3	4	5	6	7	8	9	10	11	12	E_i
0	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	00 00 00 00 00 00	E_0
1	BR BR BR BR BR BR	E_1											
2	OR OR OR OR OR OR	E_2											
3	BR BR BR BR BR BR	E_3											
4	OR OR OR OR OR OR	E_4											
5	BR BR BR BR BR BR	E_5											
6	OR OR OR OR OR OR	E_6											
7	BR BR BR BR BR BR	E_7											
8	OR OR OR OR OR OR	E_8											
9	BR BR BR BR BR BR	E_9											
10	OR OR OR OR OR OR	E_{10}											
11	BR BR BR BR BR BR	E_{11}											
12	OR OR OR OR OR OR	E_{12}											

$S_{r+b} = k \ln 54 = k \ln 3 \times 3 \times 6 = S_r + S_b + \Delta S_{\text{MIXING}}$
 $\Delta S_{\text{MIXING}} = k \ln 6$

$\langle E \rangle_{r+b} = 0 = \langle E \rangle_r + \langle E \rangle_b = 0$ ENERGY UNITS : $\langle \Delta S \rangle_{\text{MIXING}} = 0$

Table 1 (d)

ENERGY OF MIXING: IDEAL SOLUTIONS

IN CONTRAST to the entropy, the total energy does not change on mixing, if the mixing

occurs as in Table 1c and 1d. To illustrate this we assign a mass of one unit to the black balls and of three units to the red balls. The pure red ball MDB at ground level, therefore, may have energy states of 3, 6, and 9 energy units and an expected energy

$$\langle E \rangle_r = 6 \text{ energy units}$$

whereas the pure black ball MDB has an expected energy

$$\langle E \rangle_b = 2 \text{ energy units}$$

If there are no energy effects on mixing, it must follow that the energy of the mixed system

$$\langle E \rangle_{r+b} = \langle E \rangle_1 + \langle E \rangle_2 = 2 + 6 = 8 \text{ energy units}$$

The entropy function of classical thermodynamics is seen to be a monotonic measure of the number of ways that the particles that make up the system can be permuted in the energy levels available to that system.

That this is indeed the case may be seen by examining the energies of all the states in Table 1(d). The possible energy states of the mixed system range from a low of 2 to a high of 14e.u. (which is greater than the 4 to 12 range of 2 unmixed systems). Thus the average or expected energy is

$$\langle E \rangle = 8$$

$$\Delta U_{\text{mixing}} (= \Delta \langle E \rangle_{\text{mixing}}) = 0 \quad (16)$$

It also follows that, if there are no elevation changes during mixing

$$\Delta H_{\text{mixing}} (= \Delta U - \Delta(PX)) = 0 \quad (17)$$

Consequently the free energies of mixing

$$\Delta G_{\text{mixing}} = \Delta A_{\text{mixing}} = -T\Delta S_{\text{mixing}} = NRT \sum_i x_i \ln x_i \quad (18)$$

Equations (15), (16), (17) and (18) are the classical expressions for the isothermal mixing properties of ideal solutions. In fact, they define the "ideal solution."

BOTTLE AND CLASSICAL ENTROPY

A FITTING CLOSE to our entropic elucidation would be to relate "Bottle Entropy"

(Equation 7) to the classical entropy defined as

$$dS = \frac{dQ_{\text{rev}}}{T} \quad (19)$$

A general expression of S' may be written as

$$S = -k \sum_{\lambda} p_{\lambda} \ln p_{\lambda} \quad (20)$$

which reduces to equation (7) when the p_i 's all have the same constant value

$$p_{\lambda} = \frac{1}{w} \quad (21)$$

This is always true when one permutation is as likely as another because

$$\sum_{\lambda} p_{\lambda} = 1 \quad (22)$$

Furthermore it can be shown that S is a maximum when

$$p_{\lambda} = \frac{e^{-E_{\lambda}/kT}}{Z} \quad (23)$$

where k is the same constant as in Equation (7) and T and Z depend only on $\langle E \rangle$ and not on any of the p_i .

Equation (23) reduces to Equation (21) when $T \rightarrow \infty$.

From Equation (20) it follows that:

$$dS' = -k \sum_{\lambda} (\ln p_{\lambda} + 1) dp_{\lambda} \quad (24)$$

and if $\ln p_i$ is expressed in terms of Eq. (23):

$$dS' = -k \sum_{\lambda} \left[- (E_{\lambda}/kT) - \ln Z + 1 \right] dp_{\lambda} \quad (25)$$

but on substituting Eq. (22) in (25):

$$dS' = \sum_{\lambda} \frac{E_{\lambda} dp_{\lambda}}{T} \quad (26)$$

which on using Eq. (5) becomes:

$$dS' = \frac{dQ_{\text{rev}}}{T} \quad (27)$$

Thus, the function S defined by equation (20), which is related to the number of permutations of particles in accessible energy levels, or more generally to the probability of all such permutations, is seen to be the differential of the bottle analog of heat divided by T , which we recognize as the classical definition of the differential of *Entropy*.

Put another way; the entropy function of classical thermodynamics is seen to be a monotonic measure of the number of ways that the particles that make up the system can be permuted in the energy levels available to that system. It is a measure of the *freedom* enjoyed by the system's particles to move through the energy levels accessible to these particles. It also may be looked upon as a measure of the *uncertainty* associated with an assignment of the system to any one of its accessible states.

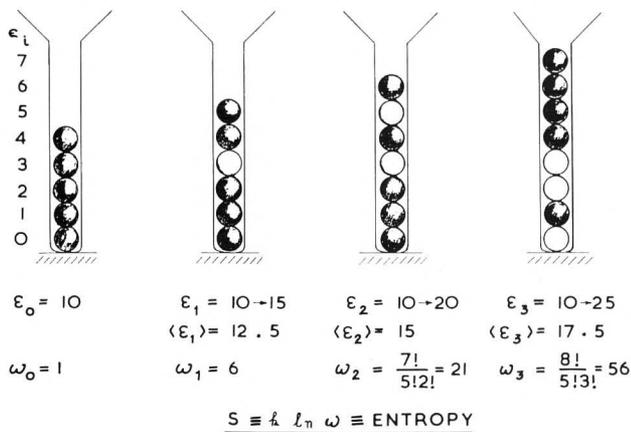


Figure 6. Seeing Entropy. Entropy is a measure of the permutability of a system. Adding white balls increases the number of energy levels accessible to the black balls and hence increases the permutations of black particles and energy levels.

RESPECTABLE DEGENERACY

WE CONTINUE OUR examination of the thermodynamics of the Maxwell Demon Bottle by looking more closely at the 252 allowed states of the 5 black, 5 white ball system. Each of these states can be described by a unique combination of 5 integers representing the 5 energy levels occupied by each of the black balls. The energy of any state "i" will be designated as ϵ_i and is given by the sum of these integers.

The individual quantum states (λ 's) are unique. The ϵ_λ , however, or not, and the number of l states that have the same ϵ_λ is called the degeneracy of energy state ϵ_λ , or w_{ϵ_λ} . Values of ϵ_λ , w_{ϵ_λ} and l for the 5 white—5 black system are shown in Table II. The degeneracy has a maximum value of 20 when ϵ_λ equals 22 or 23.

PARTITION FUNCTION

The constant Z in Equation (11) is called the *Partition Function* and can be determined by combining Equation (10) with (11), from which it follows that

$$\sum_{\lambda} p_{\lambda} = 1 = \sum_{\lambda} \frac{e^{-E_{\lambda}/kT}}{Z}$$

Therefore
$$Z = \sum_{\lambda=1}^{252} e^{-E_{\lambda}/kT} \quad (28)$$

The summation is over all possible *quantum* (l) states. Z may also be expressed as a summation over *energy*, (ϵ_i) states

$$Z = \sum_{\epsilon_i=10}^{35} w_{\epsilon_i} e^{-E_{\lambda}/kT} \quad (29)$$

in which the summation index ϵ_λ takes on all

integral values between 10 and 35 and each p_i term is multiplied by its degeneracy w_{ϵ_i} . Thus Z in Equation (27) has the same value as in Equation (26).

CONVENTIONAL THERMODYNAMIC SYSTEMS

WE HAVE TAKEN a simple set of black and white balls and ascribed to the set properties that we usually associate with thermodynamic systems. We have given the MDB an "energy" and have shown how this "energy" can be changed by "heat" and "work" effects. We have also shown that a system whose energy accumulation is the result of heat effects can do less work (has a lower availability) than a system of equal energy accumulated as the result of reversible work effects. In addition we have determined an "entropy" for the balls which is related to the number of ways the black balls may be arranged in the energy levels available to each

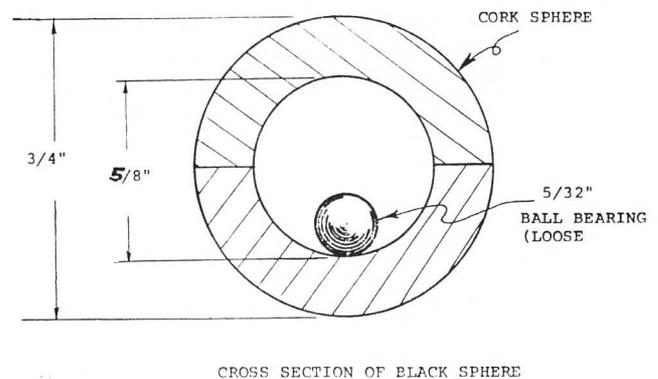


Figure 8. Cross-section of a black sphere.

black ball. We could also have derived the conventional relationships for the thermodynamic properties in terms of the partition function of the bottle. We are able to do all this because our system, like all physical systems, may be described in terms of discrete particles having discrete energy levels; and also because we have defined entropy by Equation (20). An implicit and essential part of this definition is that the p_i in equation (20) have that set of values which *maximizes* S . These p_i are evaluated by standard mathematical maximization techniques (2, 5) that take into account such constraints as Equation (22), which says that the set of states must be exhaustive; and Equation (2), which says that the energy magnitudes of all the accessible quantum states is known as is the average or expected energy of the system. The maximization

E_x	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
V_{E_x}	1	1	2	3	5	7	9	11	14	16	18	19	20	20	19	16	14	11	9	7	5	3	2	1	1	
	01234	01235	01236	01237	01238	01239	01240	01259	01269	01279	01289	01389	01489	01589	01689	01789	02789	03789	04789	05789	06789	16789	26789	36789	46789	56789
			01245	01246	01247	01248	01258	01268	01278	01369	01379	01479	01579	01679	02589	02689	03689	04689	05689	14789	15789	25789	35789	45789		
				01345	01254	01257	01267	01349	01359	01378	01469	01569	01678	02489	02679	03589	04589	05679	13789	15689	24789	34789	45689			
					01346	01347	01348	01358	01368	01459	01478	01578	02389	02579	03489	03679	04679	12789	14689	23789	25689	35689				
						02345	01356	01357	01367	01458	01468	01568	02379	02479	02678	03579	04579	05678	13689	15679	24689	34689	45679			
							02346	01456	01457	01467	01567	02369	02469	02569	03479	03678	04678	12689	14589	23689	25679	35678				
								02347	02348	02349	02359	02378	02478	02578	03569	04569	12589	13589	14679	24589	34589	45678				
									02356	02357	02358	02368	02459	02568	03469	03578	04578	12679	13679	15678	23679	34678				
										02356	02456	02367	02458	02468	03459	03478	04568	12489	13489	14579	23589	25678	35678			
											02347	02457	02467	02567	03468	03568	12389	12579	13579	14678	23679	34678				
												02356	03456	03457	03458	03567	04567	12479	12678	13678	23489	24579	34579			
													02348	02349	03467	02369	02379	02569	03479	14569	23579	24678				
														02357	02358	02359	02378	02469	02578	03569	13569	14578	23678	34578		
															02456	02367	02368	02459	02478	03469	13578	23479	24569	34569		
																02457	02458	02468	02568	03478	14689	23569	24578			
																	02456	02467	02567	03459	03468	03458	03457			
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																						02457	02467	02567	03458	03467
																							02457	02467	02567	03458
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																										02457

Table II

Quantum States, Energy States and Degeneracy of the 5-Black, 5-White Sphere MAXWELL DEMON BOTTLE

procedure yields the set of p_i 's given by Equation (23), wherein the probability of a quantum state is a function of its energy magnitude (except at infinite temperature).

Equation (20) provides a formalism for assigning p_i 's in an objective fashion. We, therefore, need not hypothesize ergodic behavior and have no difficulty establishing the thermodynamics of a five, or, for that matter, a single particle system.

It is interesting to note that the MDB particles behave as "Fermions" that is, like electrons, in that two particles can not occupy the same quantum level. The diameter of the neck of the bottle imposes a "Pauli Exclusion Principle" on the system.

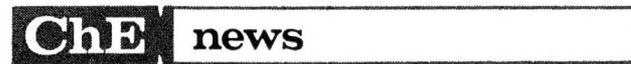
AND IN CONCLUSION: THE MAXWELL DEMON

THE READER MAY have wondered how does one get the bottle back to the state of Figure (1) in preparation for a repeat demonstration. One could, of course, make repeated trials and trust to chance that the initial state would be restored. But how much nicer it would be to call upon Maxwell's Demon to perform the separation for us. It was alleged at the beginning of this article that the Demon is sealed within the bottle. To demonstrate that this is no empty allegation, and to invoke the Demon, one grasps the flask at the base of the neck in a neck-up position as in Figure 2 and swirls its contents using a circular wrist motion. Then the flask is turned to the neckdown position while the swirling is continued so that the spheres are held in the body of the flask by centrifugal force. On reducing the rate of swirling, the spheres rolling inside the flask body follow a spiral path into the neck with the black spheres falling into the neck before the white ones. The "Demon," or whatever other name one may wish to give this gentle deception, lies in the black spheres which are constructed so

as to lose momentum rapidly. A "demon" design that has worked satisfactorily is shown in Figure 8. Commercially bottled demons are available, (3). □

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ENVIRONMENTAL CONFERENCE AT WORLD'S FAIR

Washington State University will sponsor a three-day conference, "Environment and the Economy: Exploring the Tradeoffs," in Spokane September 5-7 in cooperation with the world environmental fair, EXPO '74.

Program chairman for the conference is Dr. Joseph Brink, chairman of the WSU Chemical Engineering Department. The meeting will be managed by the Engineering Extension Service.

According to Brink, the agenda will focus on the interface between the environment and the economy, the benefits and limits of growth, land use, costs of pollution control, the political framework as it relates to energy, resources, and recycling.

Among the featured speakers will be Donald P. Hodel, Bonneville Power administrator; Dr. Eric Farber, solar energy researcher, University of Florida; Brock Evans, Sierra Club, Washington D.C.; Dr. John McKetta, chemical engineer, University of Texas; and Dr. Roger Cortesi, director of the Washington Environmental Research Center of the Environmental Protection Agency. □



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