



chemical engineering education

VOLUME XXIV

NUMBER 3

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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

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also . . .

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ORAZEM, SHAH

Problem: Drainage of Conical Tanks With Piping
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Stochastic Modeling of Chemical Process Systems: Part 3
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Introducing the Concept of Film Heat Transfer Coefficients
FIELD

An Open-Ended Problem in Chemical Reaction Engineering
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Plasmid Instability in Batch Cultures of Recombinant Bacteria
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Introducing Applications of Biotechnology to High School Students
WISE, BUONOPANE, BLACKMAN

and . . .

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ChE department

AUBURN UNIVERSITY

BELINDA DICKMAN, ROBERT P. CHAMBERS
Auburn University
Auburn University, AL 36849-5127

Auburn University is the largest, most comprehensive university in Alabama and is the state's major graduate school for students in engineering, agriculture, physical and biological sciences, veterinary medicine, and many other areas of study. During the fall quarter of 1989, the College of Engineering had 3,769 students, placing it among the top twenty largest colleges of engineering in the nation.

Auburn first offered courses in chemical engineering in 1913, and the first class of MS chemical engineering graduates received degrees in 1919. The doctoral program began in 1974 and the professional mentors program in 1986. Women have been earning chemical engineering degrees at Auburn since the early days of the program.

The program at Auburn has consistently attracted large numbers of excellent undergraduates. In 1989, the chemical engineering department had a freshman class of 123, the fourth largest in the United

States as measured by the enrollment survey taken at the 1989 AIChE meeting in San Francisco. A freshman class of that size translates into a senior class of about eighty, which is significantly higher than the expected 1990-91 graduating class of about fifty.

Auburn has one of the largest graduate programs in the Southeast. It experienced dramatic growth during the 1970s and 1980s and is becoming a significant program at both the doctoral and the master's levels. There are twenty-seven new full-time graduate students as of fall 1990—an increase from the previous average of twenty new graduate students per year. Approximately three-quarters of these new students are earning their PhDs. The total fall 1990 full-time graduate enrollment is eighty, and there are fifteen part-time graduate students working toward a master of chemical engineering degree.

Auburn chemical engineering students are heavily recruited. Last year, more than 125 companies interviewed BS, MS, and PhD chemical engi-

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neers through the University Placement Office, and more companies are expected next year. Employers respect and recruit Auburn graduates for their strong work ethic, high standards, and high levels of motivation.

Auburn has a history of student excellence. The high quality of entering freshmen at Auburn (with average ACT scores of 27.1 and average SAT scores of 1202) has consistently ranked the department at or near the top of Southeastern public university chemical engineering departments. Similarly, the quality of graduate students is high, with the average GRE quantitative score above 750 (out of 800). The proportion of women in the undergraduate program has risen significantly during the past decade. Minority enrollment is small, but growing; about ten percent of the undergraduates are black.

Both the graduate and the research programs have shown impressive growth, with the total value of extramural research continually exceeding five million dollars. Annual research expenditures were \$2.5 million in 1988-89, with approximately eighty percent coming from federal agencies.

The department has had seven NSF grants in the past three years. As reported in the 1989 American Chemical Society Directory of Graduate Research, our department published 103 refereed articles in 1987-88, which ranks Auburn 16th among public chemical engineering departments in the United States. Refereed publications for this year will be significantly more than in 1988.

The department received the Dow Outstanding Chemical Engineering Department Award each year since 1983. We also were awarded the Exxon Centennial Outstanding Chemical Engineering Department Award for the years 1984-1990.

The department is principally located in Ross Hall, with additional research, lab, teaching, and office spaces in several nearby buildings. Currently, the department has thirty-one research or teaching laboratories. Tennessee Eastman recently invested a substantial amount in our undergraduate laboratories, allowing us to begin upgrading and improving the facilities.

Prominent research centers which Auburn directs include the Space Power Institute (SPI), the Consortium for Commercial Applications of Space, the Pulp and Paper Research and Educational Center, the Molecular Genetics and Biotechnology Center, the Advanced Manufacturing Technology Center, the National Center for Asphalt Technology, the

Alabama Microelectronics Science and Technology Center, the Highway Research Center, and the Water Resources Research Institute.

The Space Power Institute and the Consortium for Commercial Applications of Space, which conduct space-related research programs, were established as the academic focus for the nation's space power program. Auburn is the lead university in a multi-university consortia funded by NASA and other federal agencies. Terry Baker and Bruce Tatarchuk

The program at Auburn has consistently attracted large numbers of excellent undergraduates. In 1989, the department had a freshman class of 123.

are heavily involved with Auburn's space research. In recognition of its contributions to space research, NASA designated Auburn as a Space Grant University.

At the request of pulp and paper industry leaders, the college of engineering established the Pulp and Paper Research and Educational Center (PPREC) in 1985. Industry leaders felt Auburn's significant contributions to the industry and its location in the heart of the pulp and paper manufacturing area made it the ideal university to direct the project. The goal of PPREC is to conduct research on improving productivity and profitability in the industry, to provide highly-skilled engineers, to further the application of science and advanced technology in the industry by conducting fundamental applied research with emphasis on quality and cost efficiency, to be a continuing educational resource for the industry, and to provide a facility for developmental activities in pulp and paper manufacture. The PPREC is one of the leading paper research and educational centers in the South. A. Krishnagopalan is the acting director of PPREC and coordinator of the Pulp and Paper Instructional Program in chemical engineering.

CURRICULUM

The undergraduate curriculum approved for 1991 consists of 204 quarter hours: 82 in chemical engineering, 39 in chemistry, 23 in mathematics, 8 in physics, 3 in engineering science, and 46 in liberal arts, humanities, and social sciences. Chemical engineering courses in the basic curriculum include mass and energy balances, thermodynamics, computers in

Auburn has one of the largest graduate programs in the Southeast, It experienced dramatic growth during the 1970s and 1980s and is becoming a significant program at both the doctoral and the master's levels. There are twenty-seven new full-time graduate students as of fall 1990. . . . Approximately three-quarters of these new students are earning their PhDs.

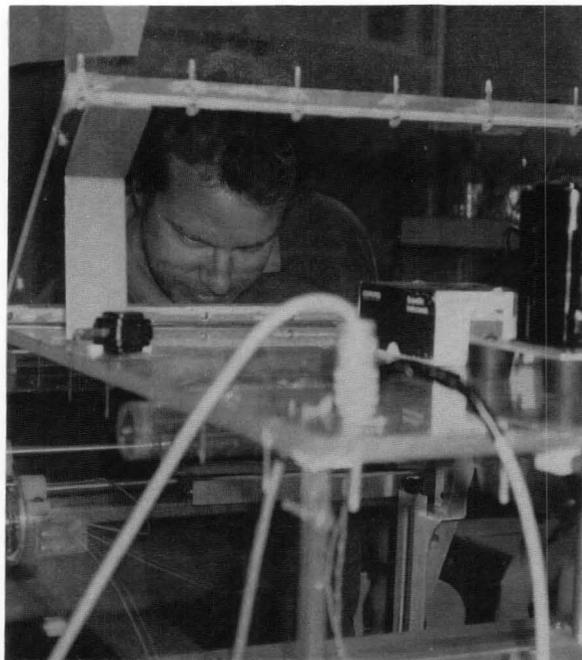
chemical engineering, fluid mechanics, heat and mass transfer, stagewise operations, reaction engineering, process design practice, computer-aided process design, process dynamics, digital process control, process economics, computer-aided process simulation, and hazardous materials management.

For students who wish to pursue special interests, the department offers options in biochemical engineering, computer-aided design and control, environmental chemical engineering, pulp and paper engineering, and pre-medicine/pre-dentistry. These options offer electives appropriate to each area plus electives in advanced materials. Students take an intensive series of laboratory courses that includes transport and thermodynamics, stagewise operations, computer-aided process control, process simulation, process design, pulp and paper engineering, surface and colloid science, senior projects, and undergraduate research. The program features numerous projects in the senior year that build upon knowledge gained in previous years' study.

The Doctor of Philosophy and the Master of Science degree programs are based on strong chemical engineering fundamentals, specialized courses, and research. Research opportunities are frequently interdisciplinary and include collaborative research in chemistry, materials engineering, electrical engineering, forestry, microbiology and genetics, pharmacy, etc. Core courses for the Master's degree program include transport phenomena, chemical engineering analysis, chemical engineering thermodynamics, and reaction engineering. Elective courses, directed reading, special topics, seminars, and a thesis complete the program.

For the PhD degree, students must complete the MS core courses plus advanced courses in numerical methods, process control, and catalysis. They must also complete the requirements of a minor, consisting of a series of courses outside of chemical engineering. The heart of the PhD program is a dissertation describing the student's original research.

The Master of Chemical Engineering Degree is a professionally oriented non-thesis degree designed for working chemical engineers to allow them to update and broaden their knowledge of the field.



Bob Himes sets up the Langmuir-Blodgett deposition apparatus.

RESEARCH FOCUS

The department has a broad and varied research focus, and most faculty members perform research in more than one area (see Table 1). **BRUCE TARTARCHUK** conducts research in catalysis and microscopic surface interactions occurring at and between solid surfaces. As part of his research, he measures fundamental surface properties using state-of-the-art spectroscopic probes. The spectroscopic probes permit the measurement of reaction, adsorption/desorption phenomena, molecular vibration and structure, and non-destructive depth-profiling of reactions at buried interfaces. Since two materials always contact at an interface or a surface measurement, understanding and control of these phenomena provide a powerful means to control surface reaction phenomena. Tartarchuk's research has application to the study and improvement of heterogeneous catalysis, thin film protective coatings, thin film solid lubricants, and new generation high energy density and high power density composite fibrous electrode material.

TABLE 1
Faculty and Research Interests

- **Terry K. Baker** *University of Wales*
Heterogeneous Catalysis • Chemical Engineering of Composites
• Heterogeneous Carbon • Controlled Atmosphere Electron Microscopy
 - **Robert P. Chambers** *University of California*
Biochemical Engineering • Biomedical Engineering • Pulp and Paper Engineering • Environmental Engineering
 - **Christine W. Curtis** *Florida State University*
Asphalt Chemistry • Catalysis • Coal Science and Conversion • Reaction Pathways
 - **Mahmoud El-Halwagi** *UCLA*
Process Design • Optimization • Process Control
 - **James A. Guin** *University of Texas*
Transport Phenomena • Catalysis • Coal Science and Conversion • Mass and Heat Transport • Reaction Kinetics and Engineering • Engineering of Asphalt/Aggregate Composites
 - **A. Krishnagopalan** *University of Maine*
Reaction Kinetics and Engineering • Pulp and Paper Engineering • Process Instrumentation • Process Control
 - **Jay H. Lee** *California Institute of Technology*
Process Control
 - **Y. Y. Lee** *Iowa State University*
Biochemical Engineering • Biotechnology • Biomass and Pulp and Paper Engineering • Reaction Kinetics and Engineering
 - **Glennon W. Maples** *Oklahoma State University*
Combustion • Energy Conversion and Use • Thermodynamics • Utility Systems
 - **Ronald D. Neuman** *The Institute of Paper Chemistry*
Interfacial Phenomena • Pulp and Paper Engineering • Solvent Extraction • Surface and Colloid Science
 - **Timothy D. Placek** *University of Kentucky*
Optimization • Process Simulation • Pulp and Paper Engineering
 - **C. William Roos** *Washington University*
Biochemical Engineering • Biotechnology
 - **Arthur R. Tarrer** *Purdue University*
Environmental Engineering • Catalysis • Coal Science and Conversion • Mass and Heat Transfer • Process Control • Reaction Kinetics and Engineering • Engineering of Asphalt/Aggregate Composites
 - **Bruce J. Tatarчук** *University of Wisconsin*
Catalysis • Chemical Engineering of Space Systems • Reaction Kinetics and Engineering • Surface Science • Materials Science
- Part-Time, Visiting, and Adjunct Faculty**
- **George Emert** Adjunct - Auburn University Executive Vice President (Virginia Tech) Biotechnology • Biomass • Applied Microbiology
 - **David Hart** Adjunct - of Rust Engineering (University of Alabama) Process Design • Plant Design
 - **James P. Henley** Visiting (University of Mississippi) Application of Expert Systems to Process Control
 - **Leo J. Hirth** Part-Time (University of Texas at Austin) Process Simulation and Design
 - **Donald Vives** Part-Time (Columbia University) Thermodynamics
 - **David Whitman** Visiting (Auburn University) Biomedical Engineering

TERRY BAKER performs research in composite materials, gasification/protection of carbonaceous materials, carbon filaments in energy storage devices, fundamental aspects of catalytic carbon formation, carbon deposition of metal catalysts, metal support interactions, and physical and chemical properties of small particles. His research in composite materials will have application to such things as production of a three-dimensional preform for use in automotive and aerospace structures. As part of his research with SPI, Baker is investigating the use of carbon composites in aerospace applications where materials are expected to survive and maintain their integrity in a variety of hostile conditions. He is also examining the use of carbon as electrode material in capacitors. In his metal support interactions research, he is studying ways of tailoring the structure of catalysts to control the pathways so that the yield of a desired product from a given reaction can be maximized.

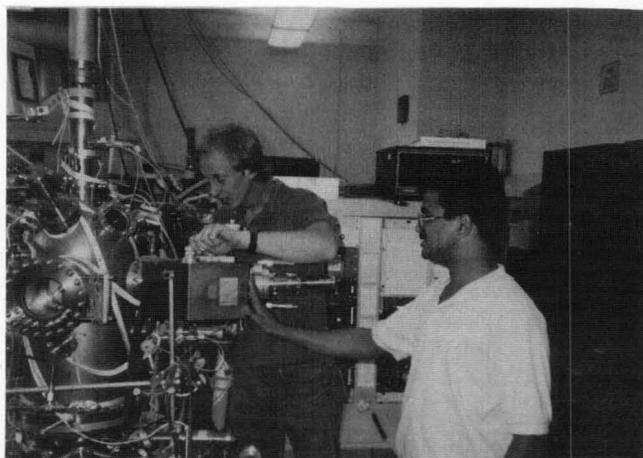
RONALD NEUMAN conducts research in surface and colloid science. Currently, he is studying monolayers, or monomolecular films, which can be used to model various interfacial systems and processes. Monolayer studies are important because physical, chemical, and biochemical process rates often are affected by materials, such as surfactants or surface-active agents, that concentrate at phase boundaries. By studying monolayers, Neuman can extrapolate information about interfacial behavior and interactions of surface-active molecules. Monolayers permit him to perform experiments on a well-defined controlled interfacial system. His unique approach to the study of monolayers or monomolecular films is his use of laser techniques. He is developing and applying advanced laser techniques to monolayers at fluid/fluid interfaces. Progress in obtaining fundamental information in classical surface chemical approaches has become more difficult, but Neuman eliminates this difficulty with the use of sophisticated, recently-developed laser techniques. These techniques hold promise for significant advancement in understanding the molecular processes underlying interfacial phenomena and systems. Neuman is also measuring the thermodynamics and transport properties of surface films. His research will have applications to solvent extraction, membrane technology, food emulsion technology, and papermaking.

A. KRISHNAGOPALAN is the primary researcher in the pulp and paper area. His research explores ways of increasing productivity and profitability in the industry. His major interests lie in computer-aided process control, advanced pulping

and bleaching technologies, paper coatings, and composite materials. He also hopes to develop an improved kraft digester control method. His new control approach will reduce errors caused by feedforward predictors and will allow the effect of certain process disturbances to be estimated and counteracted. He hopes to apply this type of controller to a large digester.

Computer-aided process simulation is the focal point of **TIMOTHY PLACEK**'s research. He is developing an Advanced Simulator for the Pulp and Paper Industry (ASPPI) to assist the engineer in decision-making and to increase efficiency in the industry. Placek decided to develop ASPPI in response to a lack of state-of-the-art technology in computer capability in modeling paper mills and pulp mills. Current software was developed for mainframe computers and does not translate well to the new microcomputers in use today. ASPPI's user interface allows the engineer to use mice and pointing devices on the screen to "blend" into and become part of the simulated process. It is also more user-friendly than other software on the market. It uses process terminology to represent specific areas; the engineer is allowed to use a name of his choice, such as the actual name of the piece of equipment. It also detects errors made during data entry, as opposed to the current software programs where the engineer must spot the errors after completion of simulation. ASPPI will give the engineer more complete control of the process, eliminate costly errors, and save time.

Christine Curtis, James Guin, and Arthur Tarrer are the principal investigators in coal science, energy conversion, and asphalt adhesion and absorption. **CHRISTINE CURTIS** works with NCAT to examine the causes of asphalt deterioration on highways and is studying asphalt adhesion in particular. She hopes to determine what part of the asphalt adheres to the rock, and once she identifies the components that adhere, she can modify, improve, and promote the adhesion process. She also hopes to modify the surface of the aggregate to increase the adhesion of the asphalt so the adverse affects of certain weathering conditions can be minimized. Curtis is also performing coal coprocessing research. She explores how hydrogen in solvent affects the coprocessing results. Through a model systems approach, she examines the fundamental chemistry involved in high temperature and pressures of coprocessing. With an actual systems approach, she changes the chemistry of the resid by catalytically reacting and pre-treating it to make the hydrogen-



Peter Lloyd (L) and Meenakshi Swaminathan check a specimen in the secondary ion mass spectrometer.

rich material more suitable for coal solvation. She hopes to improve the resid's ability to solvate coal and to transfer hydrogen to coal. She is studying model systems and exploring the interactions of various components in coal and resid on the molecular level in the presence of a catalyst.

JAMES GUIN's research applies transport phenomena and reaction engineering to the development of improved catalysts for coal and petroleum processing. Guin wants to learn more about the diffusion of large molecules in small pores of catalysts and membranes and to develop catalysts with improved pore size distribution for coal liquefaction. These catalysts have shown increased oil production using four different types of coal. He is also studying ways to prevent catalyst deactivation problems, a common problem in coal liquefaction. As part of his asphalt research, Guin is researching ways to prevent the absorption of asphalt into porous rock. Asphalt absorption can cause premature pavement failure, and he hopes to learn more about the fundamental chemistry of absorption in relation to the properties of asphalt and rock. He hopes to develop a model for asphalt construction which will help engineers construct better highways.

ARTHUR TARRER's interests lie in coal liquefaction, asphalt absorption, materials research, environmental control, and process dynamics and control. In his process research, he is developing reactor systems designed for difficult-to-control reactions. Generally, these are reactions that occur rapidly. For these reactions, it is virtually impossible to transfer reactive gases to the liquid phase fast enough to minimize undesirable reactions. Using control tech-

nology such as "bang-bang" technology, which involves switching the reaction rate from high to low and alternately switching the mass transfer rate from high to low, Tarrer will be able to control such reactions. These reactor systems will have applications to specialty chemical manufacturing, wastewater treatment, and many other processing areas. As part of his materials research, Tarrer is also developing new methodology such as techniques for testing the physical and chemical bonding strengths of asphalt pavements. He hopes to develop additives for asphalt that will reduce water-stripping and excessive absorption of asphalt into the pavement aggregate. In the environmental control area, Tarrer is working in conjunction with the EPA, the Department of Defense, and companies such as Dow Chemical and Exxon to develop waste minimization techniques to help the environment. He also currently operates a pilot plant facility that recycles about 100,000 gallons of waste oil by reprocessing it into reusable products such as specification grade fuel oil. One way that Tarrer uses his process control expertise is to interface digital programmable controllers to processing unit operations such as those used in waste oil recycling pilot plants.

GLENNON MAPLES conducts research in equipment failure detection techniques, equipment performance, and energy use. He hopes to develop methods to detect equipment failure and to evaluate the performance of the equipment, including how the variables relate to the desired output. His research in energy use allows him to measure the energy used by various machines and to evaluate methods of energy optimization.

ROBERT CHAMBERS and Y.Y. Lee are the principal researchers in the biochemical/biomedical area, and both also perform pulp and paper research. Some of Chambers' research involves enzyme engineering—alcohol detoxification in particular. Research is aimed at a fundamental understanding of the interaction of the multi-enzyme system with the physiological system of the body and on further development of the multi-enzyme system. Chambers is also investigating the use of semi-permeable microcapsules and semi-permeable hollow fibers for use as novel bio-reactors in the treatment of chlorinated organics present in the effluent produced in paper mills.

Y.Y. LEE's specialty is biochemical engineering, but he also conducts research in the areas of transport mechanisms in cellulosic biomass and

energy conversion. Lee hopes to achieve a high-yield and efficient conversion of biomass into alcohols by way of novel bioreactor/separator systems. He is also developing a process in pulp and paper by applying a low-water processing concept. Two of the problems faced by the pulp and paper industry are how to minimize production losses and how to treat mill effluent so it will minimally affect the environment. Lee hopes to reduce the water input in the pulp digester and to use a sulfur-free pulping reagent to minimize negative environmental effects. This approach will greatly reduce polluted effluent and will result in reduced chemical costs, sulfur-free processing, increased production yields, unbleached pulp brightness, and adaptability.

C. WILLIAM ROOS' work is in the separation of high-value fermentation proteins. He hopes to identify and quantify the factors which limit the rate and capacity of solid-liquid affinity chromatographic systems for large-scale application to protein separation. He also hopes to develop a concept for separating proteins to combine affinity-complex formation with membrane separation.

MAHMOUD EL-HALWAGI performs research in process design, process control, and optimization. In particular, he is researching a unified approach to the synthesis of general separation networks, synthesis of reactor-separator networks, hazardous waste minimization through chemical process synthesis, and mathematical modeling and optimization of fluidized-bed combustors.

JAY H. LEE conducts research in process control, control structure selection for large-scale systems, design and control of chemical processes, and identification and inferential control via neural networks. He concentrates mainly on his process control research; his goal is to design modern process control systems that will make significant improvements in the economics, safety, and flexibility of plants.

LOOKING AHEAD

Because of the continued growth of the program at Auburn, plans are underway for a new chemical engineering building that will house state-of-the-art laboratories. Our large, well-funded research program can support many graduate students and we welcome applications from qualified students. We also encourage undergraduate applications to our program. □

A ONE-HOUR PROFESSIONAL DEVELOPMENT COURSE FOR CHEMICAL ENGINEERS

MARK E. ORAZEM, DINESH O. SHAH

University of Florida

Gainesville, FL 32611

IN THE EARLY DAYS of our profession, many departments had a technical course to orient students to the industrial world before graduation. Courses of this nature fell out of favor, however, and now only a few departments have courses solely intended to ease the transition of seniors into the marketplace. Some of the material has, of course, been incorporated into other courses, *e.g.*, design or engineering economics. At the University of Florida, the senior seminar continues, although a humanistic emphasis was introduced in the 1970s by inclusion of topics such as interviewing skills and engineering ethics.

This one-hour course is required for all graduating seniors and is usually taken at the beginning of the last year of classes. The goals of the course are: to prepare the student for interviews and for career decisions; to develop an awareness of ethical choices; to develop an awareness of professional concerns such as chemical toxicity and patent law; and to develop skills

in presenting technical information in short talks. In a sense, this is a capstone course for the professional development of our students in much the same way that design or unit operations laboratories provide a capstone for their technical development. To our knowledge, this type of course is not at all common, and we believe that similar offerings should be seriously considered by other departments.

CLASS STRUCTURE

The structure of the course closely followed a syllabus developed and used by John O'Connell when he was in this department. The final class schedule for a group of sixteen seniors is presented in Table 1, and

TABLE 1
Schedule: Professional Development Course

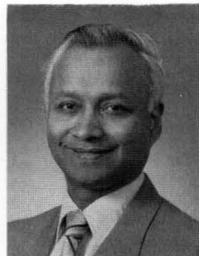
Session Topic

- 1 Organizational meeting and introduction
- 2 Self analyses—careers • Open-ended discussion of possible criteria to be used in selecting the ideal job. Assignment I due. Assigned listing of personal top ten criteria for selecting a job.
- 3 Interview preparation • Open-ended discussion of possible criteria to be used in selecting the ideal job applicant. Assigned interview partners and companies to be represented. Assignment II due.
- 4 Interviews (role playing)
- 5 Interviews (role playing)
- 6 Interviews (role playing)
- 7 Graduate School • Guest speaker, graduate school coordinator.
- 8 Ethics and Values • Assignment III due
- 9 Ethics and Values
- 10 Chemical toxicity • Guest speaker from Division of Environmental Health and Safety
- 11 Inventions and patents • Guest speaker, patent attorney
- 12 Individual talks
- 13 Individual talks
- 14 Individual talks
- 15 Individual talks
- 16 Individual talks • Closure

Mark Orazem is associate professor of chemical engineering at the University of Florida, where he contributes to Microfabritech (a center for study of electronic materials). He holds BS and MS degrees from Kansas State University and a PhD from UC Berkeley. His research interests include electrochemical systems, corrosion, and semiconductors.



Dinesh O. Shah received his undergraduate training at the University of Bombay and his doctoral degree from Columbia University (1965). In 1970 he joined the chemical engineering faculty at the University of Florida, and is currently serving as chairman of that department. He is also the Director of the Center for Surface Science and Engineering and is a professor of anesthesiology and biophysics. His research centers on interfacial phenomena in engineering and biomedical systems.



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the homework assignments are presented in Table 2. The objectives of the course follow.

● **To prepare the student for interviews and for career decisions.**

A number of homework assignments and class exercises were selected for this purpose. The initial assignment required that the students write a five-page paper on their goals in life and the aspects they considered to be important. We wanted the students to think of their careers and their lives after graduation in terms of their objectives rather than in terms of fitting into their perceptions of a recruiter's needs. This was reinforced by a class discussion on criteria to be used in choosing an "ideal" job. The instructors served primarily as moderators and recorders of suggestions put forth by the students, and concluded the exercise by requesting that students give us their top ten criteria for selecting a job. The results were compiled in the same way that NCAA (basketball or football) teams are ranked, and this compilation (shown in

Table 3) was returned to the students.

On the third day of class, a discussion was initiated in which the students were asked to consider the criteria they would use in selecting the best candidate for a job. We were now asking our students to put themselves in the position of corporate recruiters; our goal was to help students consider how to put their best foot forward. Note that throughout these discussions and, indeed, throughout this class, we avoided lecturing the students on what their criteria *should* be. Rather, we served as moderators and brought up for consideration topics and ideas that were not brought up by the students themselves.

We used the second homework assignment (Table 2) to encourage students to become familiar with the Career Resource Center (CRC) at the University of Florida. This is the university agency that handles on-campus job interviews, and our students who were looking for industrial jobs were already somewhat familiar with it. The CRC offers one-hour courses on various aspects of interviewing and professional prep-

TABLE 2
Homework Assignments

Assignment I	Write a (five-page) autobiographical paper addressing questions such as: Who am I? What is important to me? What would I like to achieve? What have I learned in college about myself?
Assignment II	Learn to use the Career Resource Center: A. Attend CRC minischool session of your choice and write a one-page outline of its content and usefulness. B. Interview role-playing.
Assignment III	Ethical Dilemmas: A. List three different technological innovations of the last fifty years which are "mixed blessings," and give at least three "good" and "bad" aspects of each development. B. Ethical problem questionnaire.
Assignment IV	Any time before the 16th session, attend a nontechnical cultural event (e.g., lecture, concert, demonstration, art exhibit). Write a one-page paper describing the activity and what you got out of it.
Individual talk	Develop and deliver a ten-minute talk on some technical topic of general (non-ChE) interest. Submit a 200-word abstract for the talk. Visual aids must be used. See handouts for more information and for a list of suggested topics.
Others	(At beginning of semester) Write a list of your top ten criteria for choosing a job or company. (Toward the end of the semester) Given the compilation of top criteria you (as a class) chose in September, list the top ten criteria you would choose now. Please indicate how, if at all, the class influenced your thinking on this.

TABLE 3
Top Twenty-Five Criteria for Choosing a Company
(Selections made at beginning of course)

This list is compiled from the top ten criteria turned in for our second class assignment. The list was obtained by allocating 10 points to the first choice for each student, 9 to the second, etc. The number in parentheses is the total for the class (16 students). Students were not given a list of alternatives; they came up with these criteria independently, and all the selections that were turned in are included here.

1.	Location (113)
2.	Salary level (95)
3.	Type of job (93)
4.	Advancement opportunities (89)
5.	Management structure and style (67)
6.	Values and ethics of company management and coworkers (50)
7.	Benefits (47)
8.	Working environment (42)
8.	Job security (42)
10.	Future growth potential (37)
11.	Support and/or opportunity for continuing education (33)
12.	Flexibility (32)
13.	Mobility within company (28)
14.	Male/female ratio (including upper management) (24)
15.	Lifestyle (21)
16.	Company reputation (15)
17.	Safety (14)
18.	Size of company (13)
19.	Emphasis on research and development (10)
20.	Sales and/or production position of company (9)
20.	Educational opportunities for children (9)
22.	Travel opportunities (6)
23.	Employee satisfaction and retention (2)
24.	Facilities (1)
24.	Feeling that the job is worth doing (1)

aration. Our students were required to take at least one of these courses (in addition to a general introductory course) and to write a brief report on its usefulness. The topics selected by the students included interviewing skills, the mechanics of computerized-interview sign-up, cover letters, job correspondence, government jobs, and resume preparation.

A large portion of class time was devoted to practice interviews. Each team consisted of two students who selected a company to represent. We asked that each group select a different company, and we tried to get a balanced representation of petrochemical, petroleum, semiconductor, and biochemical or pharmaceutical firms. The companies are listed in Table 1. The students could use any resource at their disposal (*e.g.*, the CRC, personal contacts, and talks by company representatives at student chapter AIChE meetings) to become informed about the company, and on the day of the interview a coin-toss would determine which student would be the interviewer and which the interviewee. We requested that the two students study independently to avoid a "canned presentation." We allocated ten minutes for each interview (two pairs per day) after which the class would discuss the strengths and weaknesses of each participant. The class was asked to fill out a worksheet on the participants (Table 4) which was returned to the interviewing pair.

TABLE 4
Questionnaire for Evaluation of Mock Interviews

• ROLE PLAYING INTERVIEWS •

Use the following questions to generate discussion of the mock interviews. After the instructor sees them, these sheets will be given to the interview team. Please make constructive comments.

Date _____ Company _____

Interviewer: _____

- 10 How well was the company represented?
- 10 Poise?
- 10 Knowledgeable about the company?
- 10 Project enthusiasm for the company?
- 10 Did the questions asked help distinguish among candidates? What qualities was the interviewer looking for?

Interviewee: _____

- 10 How well did the student represent him or herself?
- 10 Poise?
- 10 Knowledgeable about the company?
- 10 Positive impression as employee?
- 10 Answered questions well?
 - Name two positive characteristics that came out most clearly in the interview and two that came out least clearly.

We do plan one modification to the mock interviews. Contrary to our initial expectations, we now believe that five minutes per interview is sufficient. By the third day of interviews, the exercise became quite tedious for the spectators. In spite of this, the students (particularly those who had not interviewed before) placed great value on the experience. Some even requested a second go at it! We feel that a shorter time limit would not interfere with the amount the students learn since, inevitably, the richest interaction took place very early in the mock interview. This change will allow more time for constructive criticism and may allow us to schedule three groups per day instead of two.

A discussion of graduate education rounded out the portion of this class dedicated to career selection. While this class is required for all seniors, about twenty-five percent of our seniors choose to continue their education, and this course provided a more balanced picture of the opportunities available to them.

• To develop an awareness of ethical choices.

Our main source in this exercise was a series of articles published in *Chemical Engineering* [1-4] asking its readership to respond to a variety of real-life ethical dilemmas. We asked the students to fill out this questionnaire and then used it for two days of occasionally vehement discussions. The AIChE code of ethics was also presented, but the students were more interested in the complex problems posed by the articles. In total, the students were asked to respond on paper to eighteen different dilemmas, and the topics discussed in class were selected by the students from this list. The class discussion was augmented by examples of ethical dilemmas that the teacher had faced, and the class was encouraged to provide alternative solutions to the ones he had chosen.

It may be worth noting that the most hotly debated topic in this section was the question of who owns the knowledge of an employee. The scenario was an engineer leaving the employ of a plastics company to join a fudge-making company. Even though he had signed a secrecy agreement with the previous firm, he decides that a proprietary modification to a mixer used for plastics could be employed equally well for fudge. The question is whether divulging this new mixer design to the new company is or is not ethical. The class was evenly divided on this issue. Students on the "pro side" argued that an employee's obligation to suggest any improvements (*i.e.*, to contribute *all* his knowledge) to his current employer overrides his responsibility to his previous employer. They acknowledged that his action was illegal, but (correctly)

. . . the most hotly debated topic . . . was the question of who owns the knowledge of an employee . . . an engineer leaves the employ of a plastics company to join a fudge-making company. Even though he had signed a secrecy agreement with the previous firm, he decides that a proprietary modification to a mixer used for plastics could be employed equally well for fudge. The question is whether divulging this new mixer design to the new company is or is not ethical.

pointed out that the object of the exercise was to discuss ethics, not law. Students on the "con side" held that an employee has a legal *and* an ethical obligation to a former employer not to divulge proprietary information. When the problem was changed so that the modification was the invention of the employee, three-quarters of the class believed that employing the invention at the new place of employment was ethical. The students who felt that even under these circumstances, passing the knowledge on to the new employer was not ethical (as well as being illegal), suggested that the employee who invented the mixer could certainly make improvements to the design and thus ethically pass this improvement on to his new employer.

We spent quite a bit of time on delineating which part of our knowledge is generic and which part can be considered proprietary. Since one of the instructors (MEO) had recently come to the University of Florida after filing a patent disclosure at his previous institution, we were able to discuss how the rights of both the individual faculty member and the previous university were protected. A discussion of the legal aspects of the ownership of knowledge was led in a separate class by a lawyer from the patent division of the University of Florida.

This was a very effective and very important part of the class. We feel it is crucial to expose students to the types of ethical or moral decisions that they may face as professional engineers. Many of the problems have more to do with management than with technology, and the personal choice of a pathway through a dilemma can be supported by development of a keen sense of professionalism. In other words, ethical engineers see themselves as individuals with responsibilities to themselves, to their society, and to their profession—not as drones or cogs in a machine. Some of the comments made by our students (listed in the section "Student Comments") indicate that, through this course, they have developed a greater sense of professionalism.

An emphasis in this area has been made even more important by the recent development of the field of ethics and value studies in science and engineering which is being carried out in departments of philosophy and/or social sciences (see, *e.g.*, reference 5). This development is, in part, a response to the vacuum caused by the reluctance of technical people

TABLE 5

Topics Chosen by Students for Individual Talks

What is a Semiconductor and How is it Used?
Earthquake Prediction
Technology Involved with the Sail Design of the Stars and Stripes
Gene-Splicing Using Recombinant DNA
The Greenhouse Effect
Supernovas and Life
The Difference Between Stocks and Bonds
Solar Energy
The Role of Government in Scientific Research and Education
Plastics Pollution
How Foreign Nationals Can Stay in the United States
Black Holes
The Mechanism of Vision
Radon Gas: What It Is and What Can Be Done About It
Bhopal: Role of Government/Industry in the Aftermath of a Disaster

to get involved in matters of public policy. We believe that it is important that leadership in this area be provided by engineers and scientists who can be knowledgeable in *both* the technical and the managerial aspects of the problem. The treatment of ethical questions in this course represents a small contribution to this essential area.

The major change we recommend in the way this material was handled is the reduction of the number of problems covered in order to allow for more depth. The students could be asked to consider about nine dilemmas, and to examine perhaps four in depth. We plan to include an additional assignment requiring the students to write a workable code of ethics for engineers.

• To develop an awareness of professional concerns.

The two topics covered under this heading were chemical toxicity and patent law. Guest speakers from within the university were found for both topics. As mentioned above, a portion of the attorney's talk was devoted to the legal ramifications of the problem posed on ownership of knowledge.

• To develop skills in presenting technical information in a short talk.

The final portion of the class was devoted to ten-minute presentations by the students. The topics were to be of a technical nature, but not directly related to chemical engineering. A list of the topics chosen is

presented in Table 5. Students were required to provide a one-page abstract at least a day in advance, and the instructor went over the abstract with the student. This was meant to be a constructive and very interactive enterprise, and no formal grade was given.

The first presentation, given by the instructor, was entitled "Tips for Technical Presentations." It covered the basic elements of successful presentations and concluded with the following:

- Give your message three times in three different ways.
- Know your audience and be prepared to modify your presentation.
- Use visual aids to help your audience follow (not to help you remember) your presentation. Two minutes per slide provides a reasonable guide for the number of slides needed for a talk.
- Write your abstract to help attract listeners.
- This is your audience, and they are here to listen to you. Enjoy it!
- Do not abuse the last item!

Presentations were critiqued by the audience, and a copy of all comments was given to each speaker.

STUDENT ATTITUDES ON JOB CRITERIA

Perhaps the results of the final exercise provide the best indication of the value of this course. On the last day of class, students were given the compilation of criteria given in Table 3 and were asked to mark, at this point, their preferences. The results are given as Table 6. We noticed a number of interesting results:

- Location was the dominant criteria in September. The desire to stay near family or in Florida was a prominent reason. But in December, the type of job became overwhelmingly more important than salary or location. This could be attributed to other experiences (such as plant visits) as well as to the influence of the course.
- Ethics of the company made it into the top ten in both September and December. We were pleasantly surprised by the importance the students placed on this even before our discussion of ethics in engineering.
- The importance of job security fell from September to December. Students simply do not see job security as a major issue.
- Importance of the male/female ratio fell from 14 (with 24 points) to 23 (with only one point). This was an overriding concern of several of our female students in September, but by December, they did not include male/female ratio as a criterion at all. Some had received very significant job offers

by December, and perhaps this influenced their thinking.

- Item number 24 in Table 3 (feeling that the job is worth doing) was the tenth choice of only one student in September (who, perhaps, was struggling to come up with ten solid criteria). The rise in popularity to number 7 in December is due, in part, to the inclusion of this criterion for consideration by all students.

A number of students commented that, in their view, some of the categories overlapped. Modification of Table 6 to incorporate this overlap made only minor changes in the top five.:

1. Type of Job + Feeling that the Job is Worth Doing (184)
2. Working Environment + Values and Ethics of Company Management and Coworkers (128)
3. Salary Level + Benefits (110)
4. Location (106)
5. Advancement Opportunities + Mobility within Company (93)

A similar grouping of the results in September yielded:

1. Salary Level + Benefits (142);
2. Advancement Opportunities + Mobility within Company (117);
3. Location (113);

TABLE 6
Top Twenty-Five Criteria for Choosing a Company
(Selections made at end of course)

1. Type of job (135) {previous ranking was 3 with 93 points, or 3:93}
 2. Location (106) [1:113]
 3. Salary level (87) [2:95]
 4. Working environment (73) [8:42]
 5. Advancement opportunities (72) [5:89]
 6. Values/ethics of company management/coworkers (55) [6:50]
 7. Feeling that the job is worth doing (49) [24:1]
 8. Safety (39) [17:14]
 9. Management structure and style (38) [5:67]
 10. Job security (27) [8:42]
 11. Support and/or opportunity for continuing education (26) [11:33]
 11. Flexibility (26) [12:32]
 13. Benefits (23) [7:47]
 14. Emphasis on research and development (21) [19:10]
 14. Mobility within company (21) [13:28]
 16. Travel opportunities (18) [22:6]
 17. Lifestyle (17) [15:21]
 18. Employee satisfaction and retention (15) [23:2]
 19. Size of company (13) [18:13]
 20. Future growth potential (11) [10:37]
 21. Company reputation (10) [16:15]
 22. Facilities (3) [24:1]
 23. Male/female ratio (including upper management) (1) [14:24]
 24. Sales and/or production position of company (0) [20:9]
 24. Educational opportunities for children (0) [20:9]
-

... a one-hour course devoted to the professional development of our students is a worthwhile enterprise . . . A course of this nature provides a capstone for the professional development of our students . . .

4. Type of Job + Feeling that the Job is Worth Doing (94);
5. Working Environment + Values and Ethics of Company Management and Coworkers (92).

The most significant change here is the increased importance of the categories corresponding to the type of work the students envision doing and the atmosphere in which they will be working.

GRADING SCHEME

It is difficult to assign grades in a largely non-technical course. In previous years, the grades were assigned on the basis of class attendance and homework assignments by a strict numerical formula (*i.e.*, subtract 1/2 letter grade for each unexcused absence). We found that class attendance was very good, and all students participated in the assignments. As a result, we assigned 'A's to all students. We, of course, do not guarantee this for future classes.

STUDENT COMMENTS

Students were asked to comment on how this class influenced their decisions on the criteria they would use to select a job. Most used this as an opportunity to comment on the class as a whole. Some of their responses are

- *Before I took this class I didn't think too much about these points to choose a job. Now, I'm looking at interviewing with a lot of companies, and I do look for these points.*
- *This class has certainly influenced my thinking. It has developed in me a more professional attitude in choosing a job. Yes, I still think that location and salary level should be the most determining criteria since they are so necessary in ensuring a happy life to a human and consequently affecting his ability to be efficient. But topics like hazards in industries opened my eyes to the importance of safety in a company, how serious it should be and how dangerous the consequences of lack of it could be for a company and the workers. One thing that really struck me is the criteria about ethics and values. Before this class, I always thought of an engineer as an individual that should apply his intellectual skills in the work field without any deep involvement. At the end of this class, I know that I have to develop my sense of judgement when it comes to people, and my ability to make good decisions that will allow me to be honest to myself, to my career and to the company where I will be hired.*

- *I think this course has enabled me to see that I shouldn't have a preconceived notion of "the perfect job" before I go hunting. Although I only redefined a few things in my ratings, I've become a little more open-minded when I look at a potential job opportunity.*
- *I think that this course has influenced my criteria for choosing a company. It increased my consideration of a company's values and ethics as well as consideration of general categories other than salary, type of job, and location.*
- *The ethics exercise influenced me quite a bit – it is a topic not often stressed.*
- *This course motivated me to think about the relation of my future profession with my life style.*
- *The most helpful topic was the interview preparation. I have never had an opportunity to have an actual interview and after having the in-class (practice) interviews and listening to the criticism, I tried to correct the problems which were pointed out...I believe that I will see the benefit of this course, even more, in my personal and professional life.*

CONCLUSIONS

We believe that a one-hour course devoted to the professional development of our students is a worthwhile enterprise, and, as such, should be considered by other departments. A course of this nature provides a capstone for the professional development of our students that complements the usual capstone courses for their technical development. We have suggested some minor changes to the syllabus which we plan to implement in the next session.

ACKNOWLEDGEMENT

The success of this course is due in large part to the tradition begun by John Biery and to the outline developed by John O'Connell, who is now at the University of Virginia. We wish to thank the guest speakers: Tim Anderson, Dan Endicott, and Susan Wray.

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Random Thoughts . . .

MEET YOUR STUDENTS

3. Michelle, Rob, and Art

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The scene is the AIChE student chapter lounge at a large southeastern university. Three juniors—Michelle, Rob, and Art—are studying for the second quiz in the introductory transport course. Art got the high grade in the class on the first quiz, Michelle was close behind him, and Rob got 15 points below class average. They've been at it for over an hour.



Michelle: "What about this stuff on non-Newtonian flow—I don't think I really get it."

Art: "I think we can forget it—I've got copies of Snavely's tests for the last five years and he's never asked about it."

M: "Maybe, but it's the real stuff...you want to analyze blood flow, for instance, Newtonian won't work."

A: "So what...the only blood flow we're going to have to worry about is ours on this test if we don't stick to the stuff Snavely is going to ask."

M: "Yeah, but if we don't..."

Rob: "Hey Art, is there going to be any of that Navier-Stokes trash on the quiz?"

A: "Yeah, there usually is, but no derivations—you just have to know how to simplify the equation."

R: "Rats—I hate that garbage."

M: "I've been looking through Bird, Stewart, and Lightfoot...there are all sorts of Navier-Stokes problems in there. We could try to set some of them up."

R: "Nah, too much grind—I just need to do enough to get my C, my degree, and my MG. Art my man, why don't you haul out those old tests and let's just memorize the solutions."

A: "Okay, but that may not...hey, look at this question—he's used it for three years in a row. Parts (a) and (b) are just plug-and-chug, but he throws a real curve ball here in Part (c)—I don't know how to do it."

R: "How much is Part (c) worth?"

M: "Never mind that—let me see it.. Okay, he's asking about velocity profile development—you just need to use the correlation for entrance length."

A: "What are you talking about? I never heard of that stuff."

M: "He never talked about it in class but it's in the reading. You need to calculate the Reynolds number and then substitute it in this dimensionless correlation, and that gives you..."

R: "I'm gonna grab a Coke from the machine, guys—when you get it all straight, just tell me what formula I plug into, okay?"

A: "Yeah, sure. So it's just this correlation, huh Michelle—do I need to dig into where it comes from?"

M: "Probably not for the test, but I was trying to think why you would want to know the entrance length, and it seems to me that if you're designing a piping system that has a lot of short pipe segments it would be important to know how well your pressure drop formulas will work...blood flow again, in capillaries, or maybe lubricating oil in a car engine, or..."

A: "Forget it—that stuff's not going to be on this test. Even Snavely wouldn't be that tricky. Now look at this problem here..."



These three students illustrate what Entwistle [1] calls *orientations to studying*. Michelle has a *meaning orientation*, Rob a *reproducing orientation*, and Art an *achieving orientation*. The characteristics of the orientations are as follows:

Meaning Orientation *Michelle tends to take a deep approach to learning, meaning that she tries not just to learn facts but to understand what they mean, how they are related, and what they have to do with her experience. Meaning-oriented learners are characterized by an intrinsic motivation to learn ("I want to learn this material because it interests me and I find it relevant to my life") and a tendency to question conclusions offered in lectures and readings.*

Reproducing Orientation *Rob almost always takes a surface approach to learning—following routine solution procedures but not trying to understand where they come from, memorizing facts but not trying to fit them into a coherent body of knowledge. Reproducing learners are characterized by an extrinsic motivation to learn ("I've got to learn this to pass the course, to graduate, to get a good job") and an unquestioning acceptance of everything in the book and in lectures. They often do poorly in school.*

Achieving Orientation *Art's primary goal is to get the highest grade in the class, whatever it takes. Achieving learners take a strategic approach to learning, which involves finding out what the instructor wants and delivering it—digging deep when they have to, staying superficial when they can get away with it.*

Sooner or later most faculty bull sessions lapse into complaints that most of our students are Robs and pitifully few are Michelles. Unfortunately, few of us do anything in class to stimulate our students to take a deep approach: we just give them tricky tests to see if they can "do more than plug in," and then gripe that they're apathetic and incompetent when they can't. Fortunately, there's something we can do besides complain. The following conditions in a class have been shown to increase the likelihood that students will adopt a deep approach to learning [1,2]:

- **Student-perceived relevance of the subject matter.** *Students will not struggle to achieve a deep understanding of material that seems pointless to them, any more than we would. To motivate them to do it, let them know up front what the material has to do with their everyday lives (e.g., fluid flow in their cars and circulatory systems, heat and mass transfer and reaction in the atmosphere and their homes and respiratory and digestive systems) and with significant problems they will eventually be called on to solve (e.g.,*

fabricating improved semiconductors, developing alternative energy sources, avoiding future Bhopals).

- **Clearly stated instructional objectives, practice, and feedback.** *Students are not born knowing how to analyze deeply, and little in their precollege experience is likely to have fostered that ability. To get them to pull meaning out of lecture material and to solve problems that go beyond those in the text, spell out these objectives and give concrete examples of the kind of reasoning desired. Then explicitly ask the students to carry out deep analysis in class and on homework and give them constructive feedback on their attempts.*
- **Appropriate tests.** *Provided the preceding conditions have been met, include questions that call for deep analysis on all tests. If the students know they will only get surface questions (closed-ended exercises that require only standard solution procedures) they will likely take a surface approach to learning the material. If they expect some deep questions (more open-ended questions that require greater understanding), all of the Michelles, most of the Arts, and perhaps some of the Robs will see a need to take a deep approach and do so.*
- **Reasonable workload.** *If students have to spend all their time and energy just keeping up, they will fall back on a surface approach.*
- **Choice over learning tasks.** *Provide bonus problems and/or optional projects, and/or alternatives to quizzes, and/or optional self-paced study, and/or choices between group and individual efforts.*

The research indicates that by establishing these conditions we may substantially increase the number of our students who think critically about the material we are presenting, try to discover its meaning and its relationship with other material they have previously learned, and routinely question the inferences and conclusions that we present in class. Whether or not we'll know what to do with these people once we have them is a question for another occasion.

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INTRODUCING THE CONCEPT OF FILM HEAT TRANSFER COEFFICIENTS

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STUDENTS OFTEN STRUGGLE to gain an appreciation of the concept of a heat transfer coefficient even though they are familiar with the concept of thermal conductivity. An example of heat loss from single and double glazed windows (which is developed later in this paper) helps to bridge this divide; a beneficial link with familiar surroundings is established.

BACKGROUND KNOWLEDGE

Students should already be familiar with the method for calculating heat flow along a lagged bar, as shown in Figure 1. This involves a straightforward application of the following equation (which is often called Fourier's law)

$$q = -kA \left(\frac{d\theta}{dx} \right) \quad (1)$$

It is also necessary that the concept of interfacial temperature be understood. This may be introduced via the composite slab problem, which is both interesting and relevant. In this problem it is supposed that there are two slabs of equal area A , of thickness t_1 and t_2 , and with thermal conductivity k_1 and k_2 , respectively. Let the temperatures be defined by Figure 2. Now the flow of heat through each slab is the same;

therefore

$$q = \frac{k_1 A (\theta_{\text{hot}} - \theta_i)}{t_1} = \frac{k_2 A (\theta_i - \theta_{\text{cold}})}{t_2} \quad (2)$$

The interfacial temperature will rarely be known, but there are two equations, and q and θ_i are generally the unknowns. Rearrangement gives

$$\theta_{\text{hot}} - \theta_i = q \frac{t_1}{k_1 A} \quad (3)$$

and

$$\theta_i - \theta_{\text{cold}} = q \frac{t_2}{k_2 A} \quad (4)$$

Addition of Eqs. (3) and (4) gives

$$\theta_{\text{hot}} - \theta_{\text{cold}} = q \left(\frac{t_1}{k_1 A} + \frac{t_2}{k_2 A} \right) \quad (5)$$

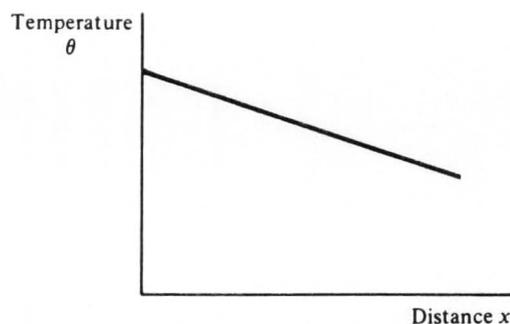
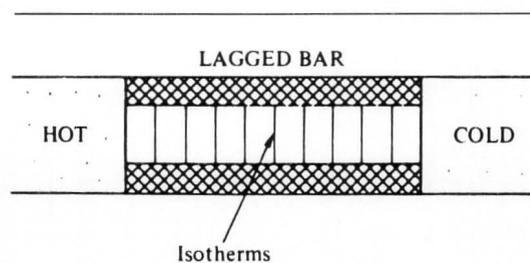


FIGURE 1. Flow of heat along a lagged bar of uniform thermal conductivity



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that is

$$q = \frac{\theta_{\text{hot}} - \theta_{\text{cold}}}{\left(\frac{t_1}{k_1 A} + \frac{t_2}{k_2 A}\right)} = \frac{(\theta_{\text{hot}} - \theta_{\text{cold}})A}{\left(\frac{t_1}{k_1} + \frac{t_2}{k_2}\right)} \quad (6)$$

This is similar to Ohm's law: q is the flow of heat instead of current; $\theta_{\text{hot}} - \theta_{\text{cold}}$ is equivalent to the driving force, the potential difference; and the t/kA terms are thermal resistances. The equation can be generalized to give the heat flow through a composite of many layers

$$q = \frac{(\theta_{\text{hot}} - \theta_{\text{cold}})A}{\left(\frac{t_1}{k_1} + \frac{t_2}{k_2} + \frac{t_3}{k_3} + \dots\right)} \quad (7)$$

where $\theta_{\text{hot}} - \theta_{\text{cold}}$ are the temperatures of the outer surfaces of the composite.

HEAT LOSS ACROSS WINDOWS

An Oversimplification

A familiar example is the loss of heat through closed windows. Students can be encouraged to estimate the loss using the above theory. For illustrative purposes, single and double glazed windows of the following specifications will be assumed: single glazed 4 mm thick glass with $k = 1.05 \text{ Wm}^{-1}\text{K}^{-1}$; double glazed

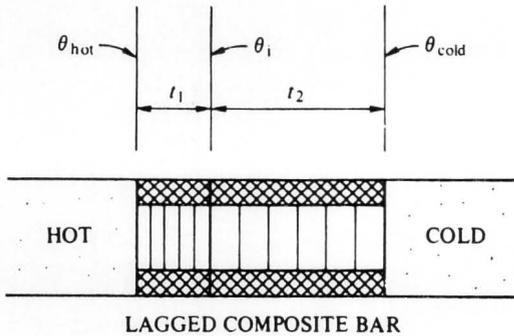


FIGURE 2. Flow of heat along a composite bar (and definition of temperatures used in text)

A familiar example is the loss of heat through closed windows. Students can be encouraged to estimate the loss . . . for illustrative purposes, single and double glazed windows will be assumed . . .

units incorporating two panes of 4 mm thick glass and a 12 mm air gap whose thermal conductivity is taken to be $0.023 \text{ Wm}^{-1}\text{K}^{-1}$. The area of glazing will be taken as 3m^2 , the room temperature as 20°C , and the air temperature as -4°C .

It could be argued that for the calculations the temperatures should be in Kelvin, not degrees Celsius. However, the numerical results are not affected since temperature differences are the same in K and $^\circ\text{C}$. This is an opportunity for pointing out that normal engineering practice does not slavishly follow the SI set of units and $^\circ\text{C}$ will be retained. Application of Eq. (7) leads to the following estimates:

$$\text{heat loss through double glazing} = \frac{[20 - (-4)]3}{\left[\frac{0.004}{1.05} + \frac{0.012}{0.023} + \frac{0.004}{1.05}\right]} = 136 \text{ W}$$

$$\text{heat loss through single glazing} = \frac{[20 - (-4)]3}{1.05} = 18,900 \text{ W}$$

The last figure is clearly excessive since 18.9kW is greater than the heat input for a whole house! If the inside surface of the pane were 20°C and the outer surface -4°C , then the heat loss would undoubtedly be in excess of 18kW. It is interesting to ask students if the temperature gradients shown in Figure 3 are reasonable.

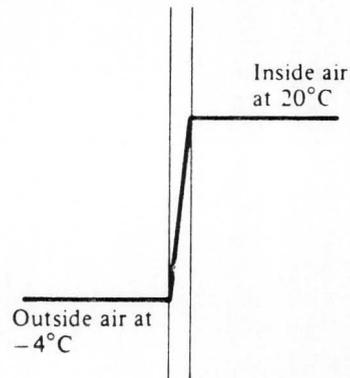


FIGURE 3. Temperature profile across a pane of glass in the absence of boundary layers

At this juncture, an opportunity arises to point out that one must be explicit about one's assumptions. Figure 3 implies that the outside air which is close to, and right up to, the window is all at -4°C , despite a large outflow of heat. Similarly, there is no temperature gradient on the room side. The model which was implicitly assumed, and which has been made explicit in Figure 3, is unrealistic. The model illustrated in Figure 4 can be introduced as being much more realistic, but still not exact. An engineer learns the importance of using intelligent approximations and of making the best possible estimate from incomplete information. In a small way this is illustrated by the current problem.

Having intuitively noted that there are regions close to both glass-air boundaries over which the temperature changes from bulk air temperature to glass temperature, it is useful to introduce a physical picture so that calculations can be performed. It may be agreed that a reasonable approximation is to assume that the air, both on the inside and the outside, can be represented by a near stagnant film or boundary layer across which there is an appreciable temperature change and a well mixed bulk which is isothermal.

It is reasonable to assume that the film thicknesses would be 2mm for the room side and 1.5mm for the outside, if the wind speed is low. A reduction to 1mm is appropriate if the wind speed is higher. Their recalculations should give the following results:

$$\text{heat loss through single glazing (low wind speed)} = \frac{[20 - (-4)]3}{\left(\frac{0.002}{0.023} + \frac{0.004}{1.05} + \frac{0.0015}{0.023}\right)} = 462 \text{ W}$$

$$\text{heat loss through single glazing (high wind speed)} = \frac{[20 - (-4)]3}{\left(\frac{0.002}{0.023} + \frac{0.004}{1.05} + \frac{0.001}{0.023}\right)} = 536 \text{ W}$$

The thicknesses and the resulting heat loss values are reasonable, and the model (which is one of pure conduction through a stagnant layer) might be of interest and, in some circumstances, of use. However the teacher will undoubtedly wish to point out that the aim is to have a value for the thermal resistance, and it does not matter if the heat loss mechanism is a combination of convection and conduction, provided an accurate estimate can be made. In the above example, the inside thermal resistance, $t/(kA)$, is $0.002/(0.23 \times 3) = 0.029 \text{ K W}^{-1}$. Taking the reciprocal (kA/t) and converting it into per area form (k/t) , one has the heat transfer coefficient. In this case it equals $0.023/0.002 = 11.5 \text{ W m}^{-2}\text{K}^{-1}$. This example has not only introduced the concept of a heat transfer coefficient but

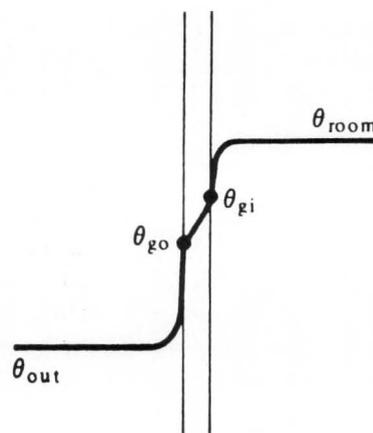


FIGURE 4. Temperature profile across a pane of glass in the presence of boundary layers

also illustrates that a balance between theory and empiricism has been productive. The insights into the physics underpinning heat transfer coefficients lead to a better theoretical understanding. The coefficients that are subsequently developed are not tied to any particular model. They can be treated as purely empirical constants of proportionality, the knowledge of which permits (given knowledge of surface area and temperature difference) the calculation of the amount of heat transferred.

While one can always find a film thickness to give a reasonable result, one can rarely predict the appropriate film thicknesses for a new situation. However, knowledge of the film thicknesses is now seen to be insignificant. In contrast, the important film heat transfer coefficients can readily be calculated from predictive equations. These enable an engineer to give an *a priori* prediction of performance under changed circumstances. The confidence attached to this prediction is enhanced if the predictive equation has some theoretical underpinning.

OVERALL HEAT TRANSFER COEFFICIENT

The above example can be used to introduce the concept of overall heat transfer coefficients. The method for combining these coefficients is similar to the method for combining thermal resistances, and an analogue for Eq. (7) will be obtained. The temperatures for the current example are defined in Figure 4. Remembering that the heat flow through the glass and the two boundary layer films is the same, the students should obtain

$$q = h_{\text{room}}A(\theta_{\text{room}} - \theta_{\text{gi}}) = \frac{k_g A(\theta_{\text{gi}} - \theta_{\text{go}})}{t_g} = h_{\text{out}}A(\theta_{\text{go}} - \theta_{\text{out}}) \quad (8)$$

where h_{room} is the heat transfer coefficient for the inside (or roomside) boundary layer, and h_{out} is the heat transfer coefficient for the outside boundary layer.

Rearrangement and addition as before gives

$$(\theta_{\text{room}} - \theta_{\text{out}}) = \frac{q}{A} \left(\frac{1}{h_{\text{room}}} + \frac{t_g}{k_g} + \frac{1}{h_{\text{out}}} \right)$$

or

$$q = \frac{(\theta_{\text{room}} - \theta_{\text{out}})A}{\left(\frac{1}{h_{\text{room}}} + \frac{t_g}{k_g} + \frac{1}{h_{\text{out}}} \right)} \quad (9)$$

The outside heat transfer coefficient will be dependent on wind speed and window position, which need to be determined, but the exact mode of heat transport (*e.g.*, the balance between convection and conduction) is unimportant and of scientific, not engineering, interest. The rate of flow of heat per unit area per unit temperature difference is

$$\frac{q}{A(\theta_{\text{room}} - \theta_{\text{out}})}$$

This is, of course, the overall heat transfer coefficient, U , and from the above equation its relationship to the individual coefficients is seen to be of a reciprocal nature

$$\frac{1}{U} = \frac{1}{h_{\text{room}}} + \frac{t_g}{k_g} + \frac{1}{h_{\text{out}}} \quad (10)$$

It may be pointed out that this is analogous to the summing of electrical resistances; the term on the left-hand side is the overall resistance to heat transfer and those on the right are the individual resistances.

DISCUSSION

It may be noted that the assumption of a stagnant layer of air between the panes of the double glazed units was also an oversimplification. The circulation currents within the enclosed space reduce the insulating effect. In order to reduce this loss of insulating power, certain manufacturers fill the space with inert gases which are several times denser than air. Frame construction also influences heat loss, and the final overall heat transfer coefficients range from 2.0 to 3.5 $\text{Wm}^{-2}\text{K}^{-1}$ for double glazed units. This compares favorably with the 7 $\text{Wm}^{-2}\text{K}^{-1}$ of typical single glazed windows, but the difference is not as dramatic as students and others first suppose.

The pedagogic value of the example is not limited to the introduction of the overall heat transfer equation. There is the opportunity to develop (a) students'

understanding of natural convection by considering in greater detail the physical process occurring in the enclosed cavity between the panes, and (b) their appreciation of forced convection by considering the effect of wind speed upon the outside film heat transfer coefficient.

ACKNOWLEDGEMENT

The author is grateful to Macmillan Education for permission to reproduce figures and items of material from the book, *Chemical Engineering: Introductory Aspects*, which was published in 1988 (ISBN 0-333-45249-6).

NOMENCLATURE

A	area
h	film heat transfer coefficient
k	thermal conductivity
q	heat flux
t	thickness
U	overall heat transfer coefficient
x	distance
θ	temperature

Subscripts

1,2	refers to slabs as shown in Figure 2
cold,hot,i	refers to cold-side, hot-side, and interfacial positions as shown in Figure 2
g	glass
gi	glass-room interface
go	glass-outside interface
out	outside
room	room-side \square

ChE book reviews

INTRODUCTION TO PHYSICAL POLYMER SCIENCE

by L.H. Sperling

John Wiley & Sons, One Wiley Dr., Somerset, NJ 08873; \$39.50 (1986)

Reviewed by
F. Rodriguez
Cornell University

This textbook is written at the level of the senior or beginning graduate student who has had no previous courses in polymers. It is presumed that a course in organic polymer chemistry will follow.

Recognition of the importance of polymers for chemists and chemical engineers has yet to be acknowledged in many departments. However, the

Continued on page 172.

Award Lecture

A RANDOM WALK IN POROUS MEDIA

The ASEE Chemical Engineering Division Lecturer for 1989 is J. L. Duda of Pennsylvania State University. The 3M Company provides financial support for this annual lectureship award, and its purpose is to recognize outstanding achievement in an important field of ChE theory or practice.



A native of Donora, Pennsylvania (a small steel mill town near Pittsburgh) Larry earned his BS in chemical engineering in 1958 from Case Institute of Technology and his PhD in chemical engineering from the University of Delaware in 1963. After graduation he joined the Process Fundamentals Laboratory at Dow Chemical Company in Midland, Michigan, as a research engineer. Eight years later he joined the chemical engineering department at The Pennsylvania State University as an associate professor and subsequently became head of the department in 1983.

He has conducted research in a wide range of fields including polymer processing, enhanced oil recovery, arctic engineering, molecular diffusion, rheology, numerical analysis of coupled transport processes, and tribology. Although these activities appear to be unrelated, most of his research involves the application of transport phenomena principles to problems involving polymers and macromolecules. He has conducted research with fifteen different members of Penn State's faculty in chemical engineering and related fields, and this work has resulted in over one hundred research articles.

Professor Duda has taught a wide range of classes in chemical engineering, including specialty courses in the polymer field and advanced transport phenomena. In addition to teaching undergraduate and graduate students, he has been the advisor or co-advisor of 35 MS and 15 PhD graduate students.

In 1980 Professor Duda received the Penn State Engineering Society's Award for Outstanding Research Achievement, and in 1981 he and a colleague (James Vrentas) were the joint recipients of the William H. Walker Award of the AIChE. He also was the recipient of a NSF Visiting Scholar grant to National Taiwan University in 1978.

J. L. DUDA
Pennsylvania State University
University Park, PA 16802

WHEN I WAS NOTIFIED that I was the recipient of the 1989 3M Lectureship Award, I was very pleased and surprised. After the initial euphoria, however, I panicked when I realized I also had to give a lecture at the ASEE National Meeting. I looked up the past lectures published in *Chemical Engineering Education*. This was a mistake! Not only did the list of authors read like "Who's Who in Chemical Engineering," but the lectures also covered a wide range of subjects. However, they could be put into two broad classifications: many were reviews of the research fields of the lecturers, while others dealt with a philosophy of education and teaching. Like most researchers, I enjoy talking about my research field, but most of my audience would probably be bored since the subject is outside the area of expertise of a general engineering audience. On the other hand, I am sure that the average engineering educator would also be bored by an hour of my philosophy on education. Consequently, I decided to combine these two general subjects in my lecture.

University professors are in the knowledge business. First, through our teaching, we transfer knowledge to our students; second, we produce knowledge for the world through our research; and third, we transfer a knowledge of how to produce more knowledge. That is, we teach undergraduate and graduate students how to conduct research. Of these three activities, I feel the third has the greatest potential for payback, yet it is the one that we essentially neglect when we discuss our profession and when we seek ways to improve our effectiveness.

The philosophical component of my lecture involves teaching students how to conduct research. To present this philosophy, I have decided to incorporate it as part of a discussion of one of my research projects. Throughout the discussion, I will utilize quotes from many other individuals which mirror my own philosophical point of

My main premise is that students often initiate their first research project with a distorted view of the research process. Students are aware of the scientific method and usually feel that research closely follows that method. However, I feel that research more closely resembles a random walk than an idealized scientific method.

view. I hope to present more than just information concerning my subject matter. I agree with J. Epstein's observation that

What great teachers teach is not just subject matter but an attitude toward it, an approach to it.

My main premise is that students often initiate their first research project with a distorted view of the research process. Students are aware of the scientific method and usually feel that research closely follows that method. However, I feel that research more closely resembles a random walk than an idealized scientific method. Students usually do not realize this when they initiate a research project, and unfortunately we educators do not attempt to dispel their illusions.

In the title to this lecture, a "random walk" refers to the reality of many research projects, and "porous media" refers to the specific topic I will be discussing—a study of the flow of polymer solutions in porous media. Many individuals contributed to the scientific content of this lecture and the most prominent were my graduate students S. K. Fan, S. A. Hong, and H. L. Wang, and my colleague, E. E. Klaus. More details of the technical aspects of this paper are available [1–4]. However, I have no one to blame except myself for the philosophical components of this lecture.

I feel that most educators fail to prepare students for their first encounter with research. Perhaps we are embarrassed by the fact that our research programs do not progress in a systematic manner paralleling scientific methods as perceived by the general public. There is no question that the body of scientific knowledge is very well-systematized. However, the production of new scientific knowledge is clearly related to artistic creativity. While we use the scientific approach to test results, when we start a project, all kinds of hurdles and false leads present themselves, and the overall process often resembles a random walk towards our well-defined objective. Nobel Prize winner Szent-Gyorgyi stated it succinctly:

Research means going out into the unknown with the hope of finding something new to bring home. If you know in advance what you are going to do, or even to find there, then it is not research at all.

Similarly, W. P. Schmitt stated:

Most studies prove that almost all truly significant inventions come outside the formal planning process.

Unfortunately, many bureaucrats who control research funding do not understand these facts. While we cannot do much about them, we *can* do a better job of preparing the researchers of the future to take on the challenge of creative research.

There is a dichotomy which new researchers have difficulty in reconciling. Although the actual process of doing research usually does not follow the idealized scientific method, we always report our results as if it did. We feel a need to report our results in the most succinct and logical manner; including all the false starts, failed experiments, and theories would only confuse and detract from the new knowledge that we want to add to the scientific and engineering base. When writing up the first research project, a young researcher should be made aware of the advice of O'Conner and Woodford:

Remember, a thesis or any scientific paper should not be the history of an inquiry, but its outcome.

In this paper, however, I am going to ignore that good advice and present the account of a project involving the flow of polymer solutions in porous media. By chronicling the actual history of this project, I hope to make new researchers more aware of the actual research process.

The main objective of this program was to develop an ability to predict the pressure drop vs. flow relationship for the flow of polymer solutions in porous media by independently characterizing the porous media and the rheology of the fluid. In essence, we wanted to develop an analog of Darcy's Law for polymer solutions. In Darcy's Law for Newtonian fluids, the porous media is characterized by the permeability, and the Newtonian fluid is characterized by the viscosity. In the flow of Newtonian fluids, the porous media is usually modeled by some sort of capillary model, and the most commonly followed approach is the one represented by the Blake-Kozeny equation as presented in Table 1. Because of the success of this approach for Newtonian fluids, it was natural that the analogous approach be considered for non-Newtonian solutions of polymers. One of the first attempts along this line was the work of Christopher and Middleman [5], presented in Table 2, in which the power law was used as a model for the fluid.

When my group at Penn State initiated this work, we developed an experimental technique in which we could actually measure the flow rate as a function of pressure drop for the flow of non-Newtonian solutions

in porous media. We initiated experiments with a well-characterized porous media and beds of uniform spherical glass beads. Review of the literature indicated that the main problems associated with the study of flow in packed beds were a result of the complications due to end effects. First of all, excess pressure drops occurred at the entrance and exit of packed beds, and the increase in porosity near the walls containing the bed caused channeling. Both of these problems were addressed in the experimental technique shown in Figure 1. By subtracting the total pressure drop across the 3-inch packed column from the pressure drop across the 6-inch packed column, the pressure dropped through 3 inches of fully

developed flow in the center of the 6-inch column could be determined. Similarly, a layer of glass beads was incorporated into an epoxy coating on the walls of the column to eliminate radial variations in porosity. This experimental technique resulted in excellent pressure drop vs. flow rate measurements for Newtonian fluids as presented in Figure 2. The straight diagonal line in the figure represents predictions of the flow behavior based on the capillary model for the porous media. The slight deviation of the data from the prediction at high Reynolds numbers is probably due to inertial effects which are not included in the capillary model.

Most young researchers would be quite pleased with results such as those presented in Figure 2 and would be ready to wrap up the project. However, two quotes are apropos at this point:

If an experiment does not hold out the possibility of causing one to revise one's views, it is hard to see why it should be done at all.

Peter B. Medawar

To limit oneself to what one can be rigorous about is

TABLE 1 Model for Flow of Newtonian Fluid in Porous Media	
Model of Porous Media	Model of Fluid
Capillary Model (Mean Hydraulic Radius)	Newtonian Fluid
Porous Media Characteristics	$\tau = \mu\gamma$
$\epsilon, D_p, \text{Tortuosity (25/12)}$	
Blake-Kozeny Equation	
$V_o = \frac{\Delta p}{L} \frac{D_p^2 \epsilon^3}{150 \mu (1 - \epsilon)^2}$	
$K = \frac{D_p^2 \epsilon^3}{150 (1 - \epsilon)^2}$	

TABLE 2 Model for Flow of Power-Law Fluid in Porous Media	
Model of Porous Media	Model of Fluid
Capillary Model	Power Law Fluid
$\epsilon, D_p, \text{Tortuosity (25/12)}$	$\tau = K\gamma^n$
Christopher-Middleman Equation	
$V_o = \frac{n\epsilon}{3n+1} \left(\frac{6\Delta p}{25KL} \right)^{1/n} \left(\frac{\epsilon D_p}{3(1-\epsilon)} \right)^{1+1/n}$	

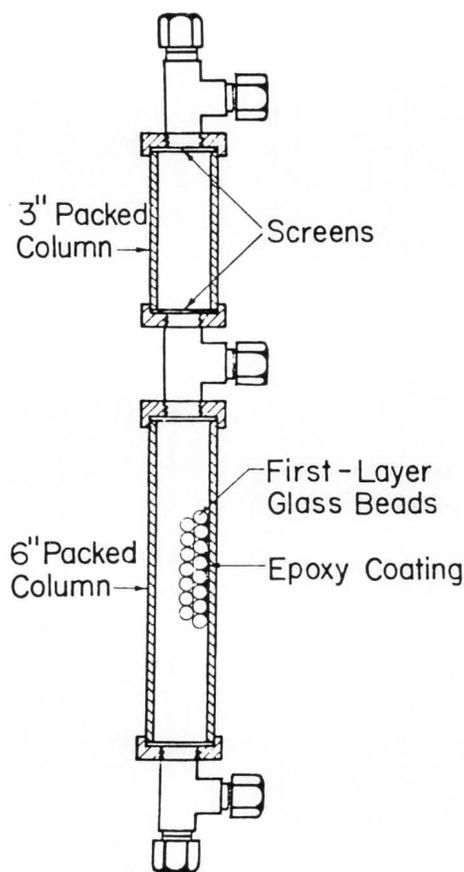


FIGURE 1. Experimental Apparatus Used to Study Flow in a Packed Column of Glass Beads.

often to limit oneself to trivial questions.

M. C. Bateson

Too often young researchers design experiments to test well-documented theories, and it is not clear what they would conclude if their experimental results did not agree with the theory. For example, if the experimental results presented in Figure 2 did not agree with the capillary model theory, would they conclude that the capillary model approach for describing the flow of Newtonian fluids in porous media is incorrect? Since that model has been evaluated by numerous investigators, I doubt that they would be willing to make such a bold statement. Instead, disagreement between the experiment and theory would probably cause them to reconsider and to modify the experiment until agreement was attained. In this case, the results of Figure 2 were used to show the validity of the experimental technique, and then the technique was used to study the flow of polymer solutions in the beds of glass spheres. Some very interesting results were attained for polymer solutions which appear to behave as purely viscous solutions and others which show elastic effects. These results are available in the literature and are not reproduced here since they would distract from the main theme of this paper.

At this point, the research group at Penn State was very pleased with the program and was prepared to

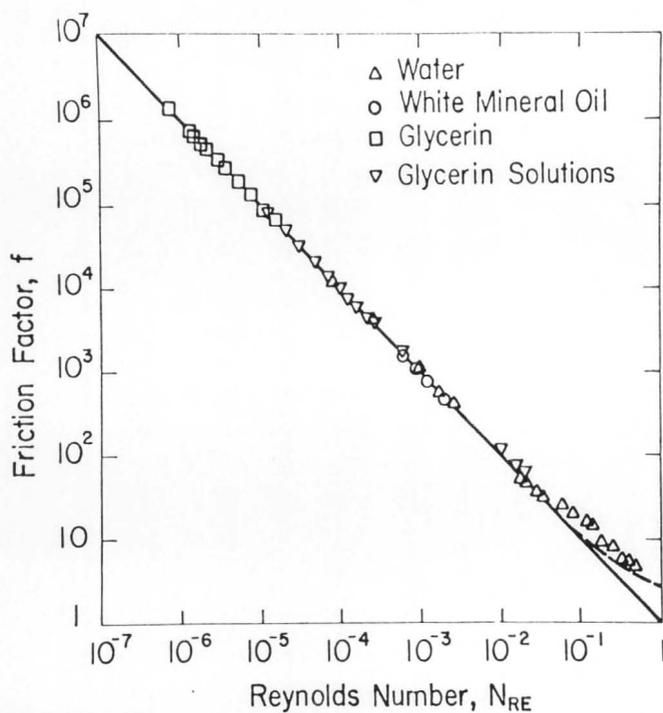


FIGURE 2. Friction Factor-Reynolds Number Relationship for Flow of Newtonian Fluids in Packed Column.

There is a dichotomy which new researchers have difficulty in reconciling. Although the actual process of doing research usually does not follow the idealized scientific method, we always report our results as if it did.

spend more time elucidating the flow of polymer solutions in the well-characterized beds of glass spheres. However, it turns out that most young researchers are not cognizant of the fact that in the shadow of every research project there lurks a sponsor. In this case, the Department of Energy was sponsoring the research (which was related to enhanced oil recovery) and the project had an industrial advisory group. This industrial advisory committee pointed out that they did not feel the study of the flow of polymer solutions through pristine packed beds of uniform glass spheres shed much light on the practical problems which involved the flow of complex mixtures of polymers, oil, electrolytes, etc., in porous rock containing clay and minerals in addition to wide variations in porosity and other characteristics. It became very clear that in order to maintain our funding we would, at the minimum, have to study flow in sandstone.

The unwanted interference of a sponsor is a reality that every researcher has to face, and the sooner a young researcher becomes aware of this the better. The key is to appreciate the interesting scientific and engineering challenges encountered along the way. In fact, in the work being reviewed here, it could be argued that the net result of unwanted sponsor interference was a greater contribution to our scientific knowledge base.

Consultations with our petroleum engineering colleagues who routinely study flow in sandstone under conditions simulating oil recovery conditions indicated that extensive new equipment would be required. The velocities in oil reservoirs are an order of magnitude of a foot a day, requiring sophisticated pumps and expensive apparatus to measure the very low associated pressure drops. Naturally, the required funds were not available in our contract! Another truism that young researchers must quickly assimilate is that sponsors always want more than they are willing to pay for!

The project faced the dilemma which is characteristic of many research programs across the country: the equipment and instrumentation were not sufficient to meet the challenge of the research. Although I would be the last to disagree with the point of view that the instrumentation and experimental infrastruc-

It is like "keeping up with the Joneses"! I feel we must warn our young researchers not to let a profusion of instruments, apparati, computers, etc., constrain their creativity or the direction of their research. The main constraint for scientific progress has been, and will continue to be, the limitations of the ingenuity and creativity of the researchers.

ture of America's colleges and universities are in critical need of an infusion of resources, I do feel that there is a tendency for hardware to take too prominent a position in our scientific endeavors. Sometimes it seems that everyone has to have a SEM, FTIR, HPLC, and a supercomputer, etc., before they can make any progress. It is like "keeping up with the Joneses"! I feel we must warn our young researchers not to let a profusion of instruments, apparati, computers, etc., constrain their creativity or the direction of their research. The main constraint for scientific progress has been, and will continue to be, the limitations of the ingenuity and creativity of the researchers.

In the project I am dissecting, the lack of funds for the "essential" equipment resulted in a breakthrough. To meet the challenge of studying flow in porous sandstone under conditions simulating oil reservoirs, my colleague, E. E. Klaus, developed a simple, inexpensive technique illustrated in Figure 3. Basically, this apparatus is analogous to an Ostwald capillary viscometer where the capillary has been replaced by a piece of porous media. The flow rate is measured by the time the fluid requires to fill a calibrated efflux bulb. The low pressure drop required to simulate re-

servoir conditions is easily attained by utilizing the head of the fluid in the reservoir above the efflux bulbs. This apparatus could be easily calibrated with Newtonian fluids to produce results which are in excellent agreement with theory. However, once these experiments were initiated with polymer solutions, several complications arose. It became apparent that large quantities of solution had to flow through the porous sandstone before steady state conditions were realized, and the permeability of the sandstone was irreversibly changed by exposure to the polymer solution. To eliminate the cost of the preparation of sandstone samples during the preliminary experiments and to enhance the probability of reproducible results, well-characterized filter paper was utilized as porous media. The permeability of the porous media was determined with a Newtonian saline solution, and then the media was exposed to a flowing polymer solution until steady state conditions were attained. Finally, the polymer solution was replaced with the original saline solution and the reduction in the permeability of the porous media was determined. Although the new experimental technique seemed to be accurate and reproducible, the preliminary results with filter

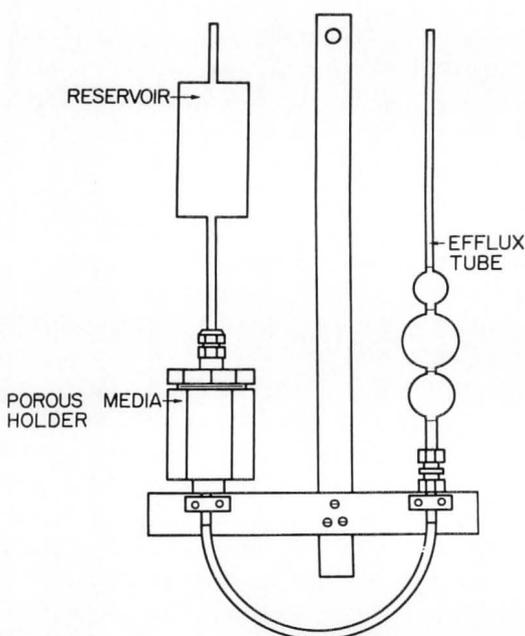


FIGURE 3. Porous Media Viscometer.

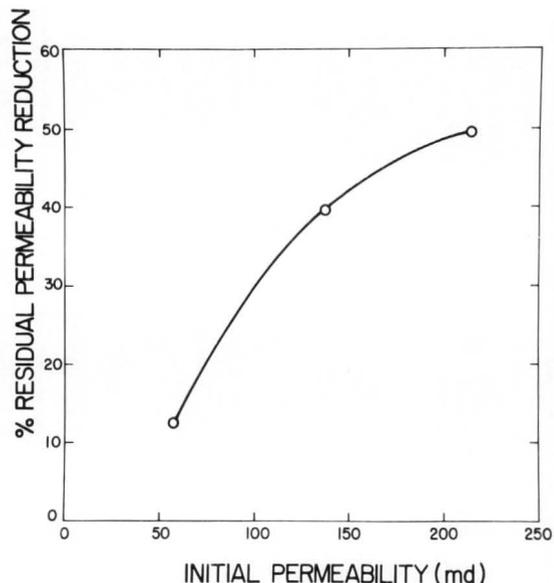


FIGURE 4. Relationship Between Initial Permeability and Residual Permeability for Flow of 500 ppm Xanthan Gum Solution Through Filter Paper.

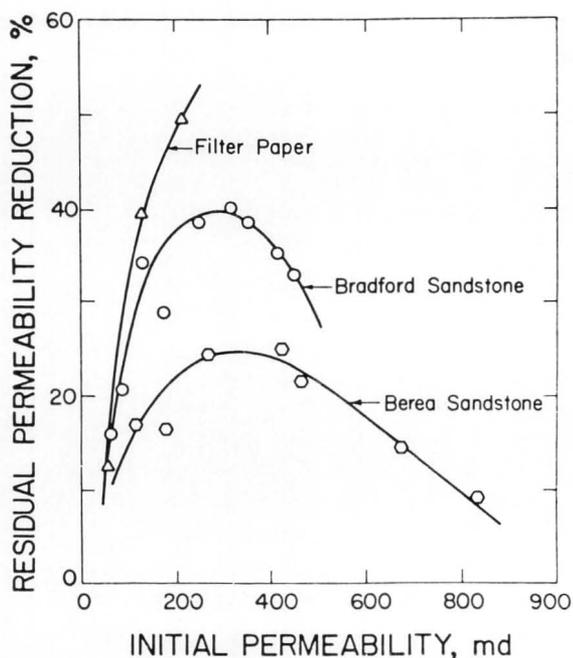


FIGURE 5. Relationship Between Initial permeability and Residual Permeability for Flow of 500 ppm Xanthan Gum Solution Through Three Different Porous Media.

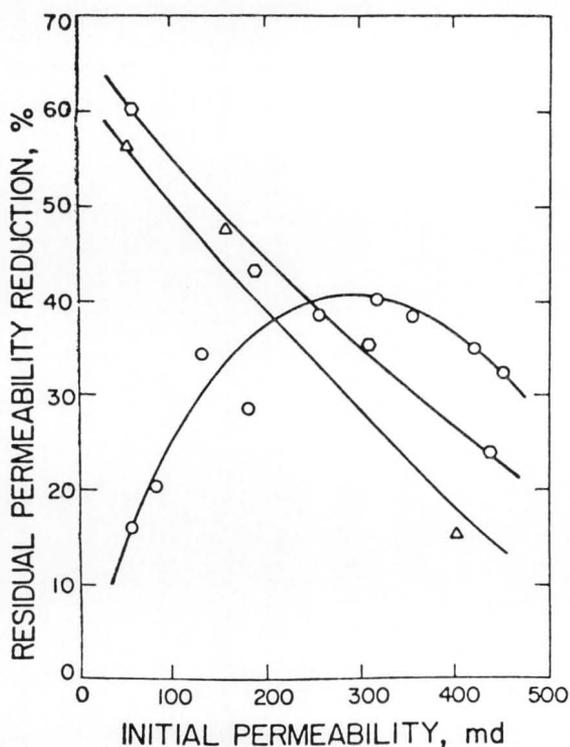


FIGURE 6. Influence of the Hydrodynamic Size of Polymer Molecules in Solutions on Residual Permeability of Bradford Sandstone. ○ 500 ppm Xanthan Gum and 200 ppm NaCl; ○ 500 ppm Xanthan Gum and 2% NaCl; △ Ultrasonic Degraded Solution of 1000 ppm Xanthan Gum and 200 ppm.

paper as presented in Figure 4 did not seem to be correct. Although the students conducting the experiments swore by the accuracy and reproducibility of the results, I concluded that the data in Figure 4 were ridiculous. Everyone agreed that the polymer molecules were irreversibly adsorbing on the walls of the porous media channels and that this caused a reduction in the permeability. However, these results appeared to indicate that thicker polymer coatings were associated with larger pores. The natural extension of this data would indicate that if we conducted experiments on a sewer pipe, we would plug off the pipe! As D. J. Boorstin said,

The greatest obstacle to scientific discovery is not ignorance but the illusion of knowledge.

Will Rogers stated the same point of view more succinctly:

It ain't what you don't know that hurts you—it's knowin' what ain't so.

Progress on this project was held up for months because of our preconceived notions of what was occurring in the porous media. Because of the limited range of the filter paper, data could not be extended beyond the range covered in Figure 4. Finally, we decided to take the bull by the horns, and we conducted experiments in actual sandstone. As the results in Figure 5 clearly show, the initial trend, which seemed to go against logic, was reversed at higher initial permeabilities, and the behavior followed the anticipated trend after a maximum was attained. Although everyone associated with the project was finally convinced that these results were real, they did not represent a contribution until a mechanism consistent with this behavior was envisioned. I think Einstein said it best:

Knowledge cannot spring from experience alone, but only from the comparison of the inventions of the intellect with the observed facts.

Like most new knowledge, the explanation for behavior shown in Figures 5 and 6 appeared trivial once it was stated. The polymer molecules could not enter the pores which were smaller than the hydrodynamic volume of the polymer chains in solution. Since the polymer did not enter the small pores, these pores did not become coated with a layer of adsorbed polymer molecules. The selective flow of polymer molecules was analogous to the phenomena which was the basis of exclusion chromatography. If this mechanism was correct, then the maximum occurring in Figure 5 should have shifted towards smaller initial per-

meabilities if the hydrodynamic volume of the polymer molecules was reduced. Since the xanthan gum used in this study was not synthesized at different molecular weights, the size of the chains of this polymer in solution were modified by two techniques. By subjecting the polymer solutions to severe mechanical agitation, the covalent bonds of the polymer chain were broken. A lower molecular weight polymer resulted from this mechanical degradation. The effective hydrodynamic size of the polymer molecules in solution was also reduced by increasing the electrolyte concentration of the solutions. The confirmation of xanthan gum chains in solution was enlarged by repulsion forces between ionized groups on the molecules. An increase in electrolyte concentration formed a double layer around these charge groups and reduced the repulsion and the effective size of the polymers in solution. The data presented in Figure 6 qualitatively confirmed this mechanistic point of view. The curve with the maximum was that obtained for the flow of the unaltered xanthan gum polymer molecules in Berea sandstone. The upper curve shows the results when the size of the polymer chains were reduced by mechanical degradation, and the third curve shows that the behavior associated with the flow of xanthan gum molecules had been contracted into smaller hydrodynamic volumes by a significant increase in the electrolyte concentration. *It is interesting to note that this behavior had not been observed previously, and probably would not have been observed if this research program had the experimental equipment which was generally believed necessary to study flow in sandstone under reservoir conditions.*

At this stage in the project, we decided that a comprehensive understanding of flow in porous media could not be realized when the complications due to the complex rheology of the solution were coupled to the complications associated with polymer-wall interaction. Consequently, the next set of experiments was conducted in porous media of high permeability where polymer chain-pore wall interactions were not significant. The original plan was to study the flow of polymer solutions under conditions where they behaved as purely viscous fluids, and then to move on to the more interesting area of viscoelastic solution. We anticipated that we would quickly confirm the applicability of capillary models to describe the flow of purely viscous, non-Newtonian fluids in porous media. The utility of capillary models for such systems had been confirmed by numerous investigators, including our own earlier studies with packed beds of glass beads. However, these elegant plans were quickly scuttled by new experimental data, and the

random-walk nature of the project continued. As T. H. Huxley stated,

The great tragedy of science—the slaying of a beautiful hypothesis by an ugly fact.

It is interesting that playwright Eugene O'Neill perhaps best describes a pitfall which is most dangerous for the older researcher:

A man's work is in danger of deteriorating when he thinks he has found the one best formula for doing it. If he feels that, he is likely to feel that all he needs is merely to go on repeating himself.

All our elegant plans and preconceptions were wiped out by the new data produced with the porous media viscometer depicted in Figure 3. Instead of following the advice and the procedure which his advisors had suggested, a new student on the project started to present the data in raw form (as shown in Figure 7) rather than presenting dimensionless friction factor as a function of Reynolds number. As Figure 7 indicates, when the pressure drop (as represented by the head of the fluid between the reservoir and efflux bulb) was plotted as a function of velocity through the porous media, the experimental measurements did not agree with the model based on the capillary model and a power law rheology.

At first, this was not disturbing since the model prediction could be modified by changing adjustable parameters such as tortuosity. However, there were no

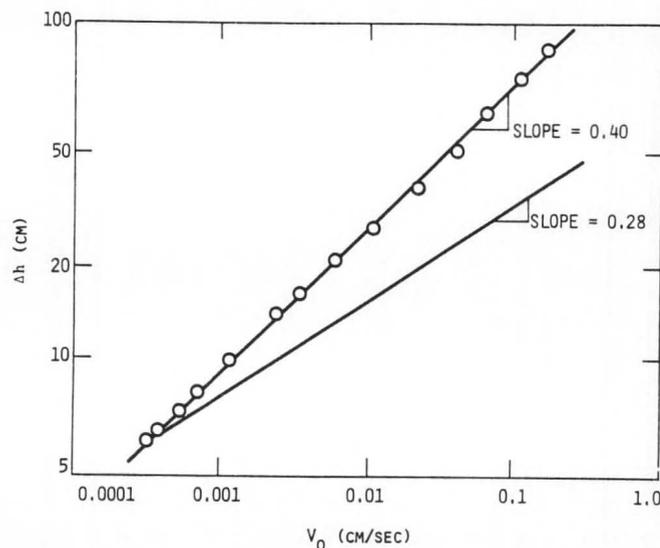


FIGURE 7. Velocity as a Function of Pressure Head in a Porous Media Viscometer for Flow of a 3000 ppm Xanthan Gum Solution Through Sandstone With a Permeability of 7.0 Darcy. Predicted Line Based on Power Law Model.

adjustments in the power law model to change the slope of the prediction lines when presented in the form of Figure 7. In other words, the line representing the prediction of the model could be raised or lowered by adjusting some parameters in the model, but the conventional model could never be adjusted to give a slope which agreed with the experimental data. At first, we assumed that this problem was due to the inadequacy of the power law model in describing the rheology of the fluid. It is a well-known fact that all polymer solutions exhibit Newtonian behavior at low shear rates and then a transition to shear thinning and power law behavior is observed at higher shear rates. Consequently, to reconcile the difference between the experimental data and the theory based on the capillary model, an Ellis model was used to describe the rheology of the polymer solutions, and the capillary model approach was coupled with this rheological equation to develop a new model. A comparison of this new model with the experimental data is presented in Figure 8. These data are representative of data obtained from many different polymer solutions. In this log-log plot, the model based on the Ellis model rheology is a curve which comes closer to fitting the experimental data but still does not represent an adequate description of the flow of purely viscous polymer solutions in porous media.

After much effort, we concluded that the limitations of the overall model were not due to the limitations of the rheological model describing the viscosity-shear be-

havior of the solutions, but were somehow inherent in the basic capillary model. This study showed that the excess pressure drops associated with the converging and diverging flow regions of any porous media must be included in a model of flow of non-Newtonian fluids in porous media. The assumption of fully developed flow, which is characteristic of all capillary models, eliminated the utilization of these models for accurately describing non-Newtonian flow in porous media. Fortunately, capillary models can describe the flow of Newtonian fluids in porous media since the pressure drops associated with fully developed flow and the excess pressure drops in the entrance and exit regions are linearly related. Consequently, a constant tortuosity factor can incorporate the effects of the excess pressure drops and the tortuosity of the flow path. However, a constant tortuosity factor is inadequate for the description of the flow of purely viscous polymer solutions or viscoelastic solutions in porous media. Finally, we concluded that two criteria were required to describe the flow of a purely viscous polymer solution in porous media.

1. The model of the porous media must include the converging and diverging nature of the porous media.
2. The rheological model of the fluid must include the transition from Newtonian behavior at low flow rates to shear thinning behavior at higher shear rates.

From these studies, we concluded that to describe the flow of polymer solutions in porous media, the model of the porous media must include converging and diverging sections. However, to describe the flow, the complete equations of motion for the non-Newtonian fluid would have to be solved for this two-dimensional flow field. If such a problem were offered to a new group of chemical engineering graduate students, it would be a very popular project indeed since it involves extensive utilization of the computer to solve a non-linear set of partial differential equations. Today we see more and more research which is based on complex numerical analysis of well-established partial differential equations such as the Navier-Stokes equations. Computers have had a very significant impact on science and engineering, and this impact will probably increase in the future. As tools, modern computers are a wonderful contribution to research. However, I feel there are problems associated with the utilization of computers (particularly by students) which are sometimes overlooked in the present environment of computer euphoria. A few quotes clearly present this point of view:

The more computer power we have, the less students

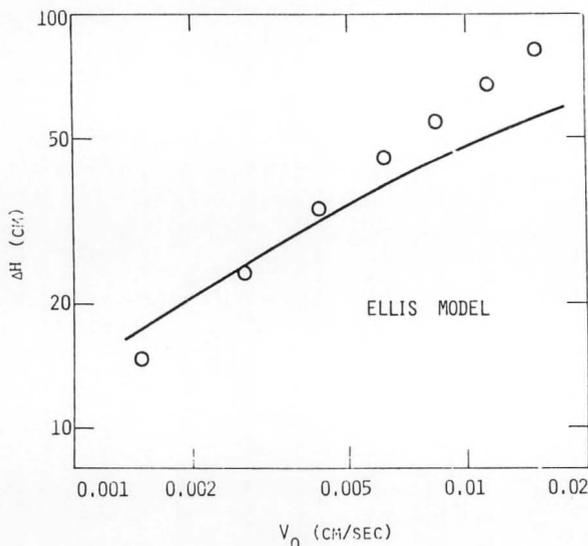


FIGURE 8. Velocity as Function of Pressure Head in a Porous Media Viscometer for Flow of a 5000 ppm Carboxy Methylcellulose Solution Through Sandstone With a Permeability of 7.0 Darcy. Predicted Line Based on Ellis Model.

know what they're doing.

Alvin White

Computers can raise a barrier to intuition.

E. Block

Several years ago, James Wei published a humorous paper in *Chemtech* concerning the number of parameters it would take to fit an elephant. A cliché among researchers is that the number of parameters in some correlations would fit an elephant. So Professor Wei went on to determine the number of parameters needed to fit the shape of an elephant. An interesting experiment is to assign the following problem to a group of students: Determine the minimum number of parameters required to produce a shape which can be recognized

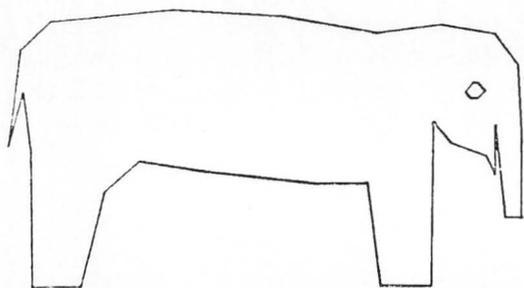


FIGURE 9. Conventional Least Square Fit of an Elephant.

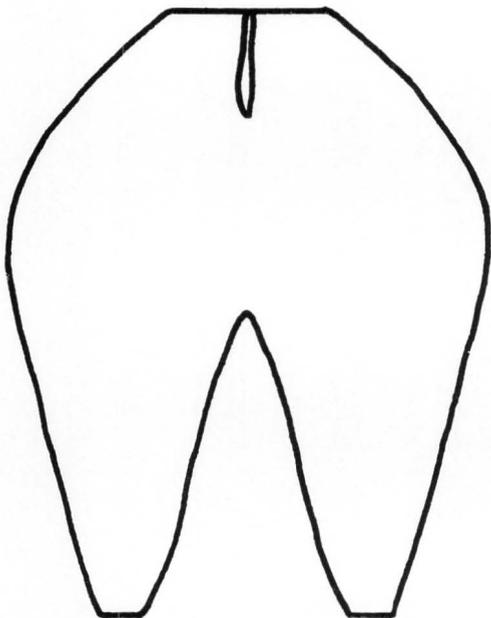


FIGURE 10. A Different Point of View!

as an elephant. Students love such a challenge since it enables them to use all the power of the computer, and it gives a sense of great accomplishment without the stress of really thinking about a problem. The students are ingenious in their ability to come up with new spline fitting techniques, the use of parallel processes, *etc.* However, they will inevitably come up with a result similar to that shown in Figure 9, and the number of parameters for all of the students will be approximately the same. Computers are touted as a great contribution to our theoretical ability. However, J. Willard Gibbs stated

The purpose of a theory is to find that viewpoint from which experimental observations appear to fit the pattern.

In other words, the purpose of theory is to find a different point of view. Computers can provide a more detailed vision, but they very seldom change a point of view. To make a breakthrough in the problem stated above, the student must think about an elephant, do a coordinate rotation, and find a line of symmetry. The resulting different point of view is presented in Figure 10. Either the front or the back of an elephant has a line of symmetry and the number of parameters needed to represent those points of view are significantly less than the usual point of view (Figure 9).

In conclusion, I feel that computers are very useful tools, but that we must train our students to recognize the danger of allowing computers to set the pace and direction of their work. They need to take time for reflection on their problems. Only then can they enjoy the benefits of the computer without falling into its empirical clutches.

I would like to express my appreciation to the 3M Company, to members of the Selection Committee, and to all those who were involved with my nomination for the opportunity to present my point of view. My collection of quotes is not well documented, and I apologize if I misquoted anyone or if I failed to give appropriate credit for material I used in this presentation.

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6. Wei, J., *Chemtech*, **128**, (Feb. 1975) □

EDITORIAL NOTE:

The following detachable pages describe some industrial employment opportunities for graduating chemical engineers. Please post the information in a conspicuous place for the benefit of your students, or distribute the pages to students who may be interested.

These companies have expressed a definite interest in hiring chemical engineers in the areas described, and we strongly encourage students seeking employment to respond as indicated.

Ray W. Fahien

Editor

Chemical Engineering Education

MILLIKEN & COMPANY

College Relations Department, M-260E

P.O. Box 1926

Spartanburg, SC 29304

● GENERAL INFORMATION ●

Milliken is a major manufacturer of textile products for apparel, commercial, home and industrial markets. Milliken Chemicals operates two modern Specialty Chemicals plants in South Carolina. The company was founded in 1865 and now has 50 plants and 14,000 associates in the US (15,000 worldwide). The Milliken environment is characterized by challenge, accomplishments, innovation, advanced technology, promotion from within based on individual performance, and extensive education and training opportunities. The chemical engineering jobs are in South Carolina and Georgia.

CITIZENSHIP REQUIREMENTS: U.S. citizenship or Permanent Resident Visa

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED: Southeastern United States

HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW: Send cover letter with functional area interests and geographic preference statement, resume, and a copy of your transcript to the above address.

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

Process Engineering: Provides technical support in textile dyeing and finishing operations and in Specialty Chemicals production. Responsibilities include manufacturing compliance with customer product quality specifications and process efficiency/improvement project assignments.

Manufacturing Management: Responsible for the production resources of people and machinery. The first line production manager may be promoted to either Advanced Production Manager or Process Engineer in the dual career ladder.

Research: Develops new products and associated machinery or processes. Prefer PhD, but will consider MS.

An Equal Opportunity Employer

DOW CHEMICAL USA

University Relations
Box 1713-CH
Midland, MI 48674

● GENERAL INFORMATION ●

Dow manufactures and markets chemicals, plastics, metals, consumer products, pharmaceuticals, specialty products and services, and agricultural products. Dow USA will hire over 200 chemical engineers in 1990 and has over 2600 chemical engineers working in all functions and geographic locations.

CITIZENSHIP REQUIREMENTS: Only U.S. citizens, aliens who have a legal right to work and remain permanently in the U.S. or aliens who qualify as "Intending Citizens" under the Immigration Reform and Control Act of 1986 are eligible for employment.

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED: Nationwide

HOW TO APPLY IF UNABLE TO SCHEDULE A CAMPUS INTERVIEW: Send resume and letter to above address, stating your job interests and geographic preferences.

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
Design	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Process Engineering	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Manufacturing	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Research and Development	BS,MS	Michigan, Texas, Louisiana, Ohio, California
Sales	BS,MS	Offices in over thirty major cities

PhD

<u>Fields of Special Interest</u>	<u>Tech Center Locations</u>
Math Modeling	Michigan, Texas, California
Polymer Processing	Michigan, Texas, California, Ohio
Polymer Characterization	Michigan, Texas, California, Louisiana
Catalysis	Michigan, Texas

An Equal Opportunity Employer

TEXACO INC.

P.O. Box 52332
Houston, TX 77052

● GENERAL INFORMATION ●

Distinguished for its worldwide integrated operations, Texaco is a leader in all phases of the petroleum industry which include exploration, producing, manufacturing, transportation, marketing, and research. Active in some 140 countries and territories, Texaco ranks as one of the largest industrial companies and employs 25,000 people in the United States.

CITIZENSHIP REQUIREMENTS: U.S. citizen or authorized to work full time in the U.S.

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED: Primarily in Texas, Louisiana, Oklahoma, California, Washington State, New York, Delaware, and Kansas.

HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW: Send resume and cover letter to:

Thomas E. Gougenheim, Manager College Recruiting
Texaco, Inc.
P.O. Box 52332
Houston, Tx 77052

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
Process Engineering	BS, MS	Texas, Louisiana, California, Washington, Delaware
Project Engineering	BS, MS	Texas
Production	BS	California, Texas, Louisiana
Research	BS, MS	New York, Texas, California
Sales	BS	Nationwide

PhD

<u>Fields of Special Interest</u>		<u>Tech Center Locations</u>
Research	PhD	Beacon, NY; Pt. Arthur, TX; Austin, TX; Montebello, CA

An Equal Opportunity Employer

UNION CARBIDE CHEMICALS AND PLASTICS COMPANY INC.

Chemical Engineering Employment Coordinator
Section M4556
39 Old Ridgebury Road
Danbury, CT 06817

● GENERAL INFORMATION ●

Our parent, Union Carbide Corporation, is a Fortune 50 Company, recognized globally for leadership in its three business groups: Chemicals & Plastics; Industrial Gases; and Carbon Products. Founded in 1917, Carbide employs 46,000 worldwide, with 25,000 in the USA. Annual sales for Chemicals & Plastics approached \$6 billion in 1989. Key UCC&P products include polyethylene, latex and specialty polymeric resins; ethylene oxide/glycol and derivatives; urethane catalysts and additives; silicones; alcohols and organic solvents.

CITIZENSHIP REQUIREMENTS: U.S. citizenship or Permanent Resident Visa (for BS/MS)

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED: Gulf coast, northeast, midwest, southeast, southwest, and Rocky Mountain

HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW: Send resume and photocopy of transcript(s) to above address. Be sure to include a cover letter specifying your functional and location preference. (See below)

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
Design (Process; Control Systems)	BS,MS	Charleston, WV
Environmental/Safety Engineering	MS	Charleston, WV
Manufacturing (Production; Env. Protection) and Process/Project Engineering	BS,MS	Bound Brook, NJ; New Orleans, LA; Houston and Victoria, TX; Charleston and Parkersburg, WV
Purchasing and Distribution	BS	Charleston, WV
R&D (Polymer Applications/Tech Service; Process Development)	MS	Bound Brook, NJ; Charleston, WV; Tarrytown, NY
Technical Sales	BS	Metropolitan areas, nationwide

PhD

<u>Fields of Special Interest</u>	<u>Tech Center Locations</u>
Catalysis, Polymers, Separations	Bound Brook, NJ; Charleston, WV

● ADDITIONAL INFORMATION ●

UCC&P has been recognized for its innovative technologies by receiving several prestigious Kirkpatrick Awards (sponsored by *Chemical Engineering Magazine*). Two of these, UNIPOL (polyolefins) and Low Pressure Oxo (alcohols), are licensed internationally and produce in excess of 15 billion lbs/yr of plastics and solvents.

An Equal Opportunity Employer

SHELL OIL COMPANY

AND SUBSIDIARIES

● GENERAL INFORMATION ●

Shell began operations in the United States in 1912. Emphasizing innovative technology and sound engineering, it has grown to be a major company employing in excess of 30,000 people throughout the United States. Chemical engineers are utilized in the recovery of oil and natural gas, refining and chemical plant operations, and sales activities.

CITIZENSHIP REQUIREMENTS: Candidates must be legally authorized to work in the United States. Will not consider candidates with student visas.

REGIONS OF USA AND/OR CANADA WHERE BS/MS CAMPUS RECRUITING IS GENERALLY CONDUCTED: Primary work locations include the Gulf Coast, California, Illinois, and Washington state.

HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW: Send resume and transcripts to
Manager Recruitment
Shell Oil Company
Department D2
P.O. Box 2463
Houston, TX 77252

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

Process Engineering: Provide technical support to petrochemical operating units, plan and develop new facilities plus major and minor revisions to existing facilities.

Computer Process Control: Provide technical support to petrochemical process control systems, including systems modification/enhancement.

Production Engineering: Optimization of oil/gas wells and reservoir performance, design and application of enhanced recovery programs, thermal recovery processes, planning and economic evaluation of operations and multiple flow analysis and application.

Chemical Sales: Provide market intelligence and customer service in support of sales efforts. Perform market research and development and market chemical and polymer products.

An Equal Opportunity Employer

OLIN CORPORATION

120 Long Ridge Road
Stamford, CT 06904

● GENERAL INFORMATION ●

Olin Corporation is a diversified company with core business in chemicals, metals, and ammunition. A Fortune 200 company headquartered in Stamford, Connecticut, Olin employs 17,000 people worldwide and has annual sales exceeding \$2 billion.

CITIZENSHIP REQUIREMENTS

U.S citizenship or permanent resident visa is required for employment

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED

Nationwide—undergraduate and PhD

HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW

Resume and cover letter to

Ms. Leah Lethbridge

Regional Supervisor, College Relations

Olin Corporation

120 Long Ridge Road

Stamford, CT 06904

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
• Sales	BS	Stamford, CT
• Business Evaluation	BS/MBA	Stamford, CT
• Development, Process, Maintenance, Production, Project	BS	Lake Charles, LA; Charles- ton, TN; Doe Run, KY; McIntosh, AL

PhD

<u>Fields of Special Interest</u>	<u>Tech Center Locations</u>
• Research and Development and Process/Production	New Haven, CT; Charleston, TN; Lake Charles, LA; Joliet, IL; Rochester, NY; Doe Run, KY; Cheshire, CT

MERCK & CO. INC.

P.O. Box 2000
RAHWAY, NJ 07065

● GENERAL INFORMATION ●

Merck & Co. is a worldwide, research intensive health products company that discovers, develops, produces, and markets human and animal health products and specialty chemicals. The company has 32,000 employees and had sales of over \$6 billion in 1989.

CITIZENSHIP REQUIREMENTS: U.S. citizen, intending citizen, permanent resident visa or otherwise authorized to work in a full-time job in the U.S.

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED: We recruit on campuses nationwide (U.S.)

HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW: Please submit resume or application which clearly states educational background, objective, and work experience to:

Theresa Marinelli, Manager College Relations
Merck & Co., Inc
P.O. Box 2000
Rahway, NJ 07065

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

	<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
	Corporate Division	BS	Rahway, NJ; Woodbridge, NJ
	Merck Sharp & Dohme Research Labs	BS/MS	Rahway, NJ; West Point, PA
	Merck Chemical Manufacturing Division	BS/MS	Rahway, NJ; Danville, Pa; Elkton, VA
	Merck Chemical Manufacturing Division	MS	Rahway, NJ; Danville, PA
	KELCO Division	BS/MS	San Diego, CA
	Calgon Water Management Division	BS/MS	Pittsburgh, PA
	Merck Pharmaceutical Manufacturing Division	BS/MS	West Point, PA

PhD

Fields of Special Interest

- Process changes which address the environmental aspects of plant operations
- Process development—from conception through to scale-up and eventual plant start up
- Chemical modification and analysis of natural polymers

Tech Center Locations

Merck Chemical Manufacturing Division
Rahway, NJ; Danville, PA

Merck Sharp & Dohme Research Labs
Rahway, NJ; West Point, PA

KELCO
San Diego, CA

● ADDITIONAL INFORMATION ●

Merck hires chemical engineers in several divisions to play a critical role in the implementation of our business.
In each division we have highly skilled chemical engineers and we will continue to hire highly qualified applicants in the chemical engineering field.

E. I. DU PONT DE NEMOURS & CO, INC.

Employee Relations Department
1007 Market Street, N-13451
Wilmington, DE 19898

● GENERAL INFORMATION ●

Established in 1802, Du Pont today is a diversified international company, strongly backed by scientific and engineering capabilities, with business operations in more than 48 countries, with approximately 140,000 employees worldwide, and with sales exceeding \$35 billion.

CITIZENSHIP REQUIREMENTS: U. S. Citizenship, permanent residency, or non-citizens who are able to work with restrictions

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED: Continental U.S.

HOW TO APPLY IF UNABLE TO SCHEDULE CAMPUS INTERVIEW: Send resume and cover letter to:

Professional Staffing Section
Employee Relations Department
E. I. Du Pont de Nemours & Co., Inc.
Wilmington, DE 19898

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

> BS/MS

	<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
	Process/Project	BS/MS	Continental United States
	Design/Manufacturing	BS/MS	Continental United States
	Construction/Distribution	BS/MS	Continental United States
	Technical Sales and Service	BS/MS	Continental United States
	Research and Development	BS/MS	Continental United States
	(Other)	BS/MS	Continental United States

> PhD

<u>Fields of Special Interest</u>	<u>Tech Center Locations</u>
Process, Project, Research and Development	Mid-Atlantic Region

An Equal Opportunity Employer

CHEVRON CORPORATION

225 Bush Street
San Francisco, CA 94104

● GENERAL INFORMATION ●

Amongst the top industrial corporations in the U.S.; the third largest petroleum company in the U.S.; one of the fifteen largest chemical operations worldwide. Approximately 53,700 employees work throughout the U.S. and 97 other countries. Involved in all aspects of the energy business: exploration, production, manufacturing, transportation, marketing, and research.

CITIZENSHIP REQUIREMENTS

Candidates must be U.S. citizens or legally authorized to work in the U.S.

REGIONS WHERE BS/MS CAMPUS RECRUITING IS CONDUCTED

Continental U.S.

HOW TO APPLY IF UNABLE TO SCHEDULE A CAMPUS INTERVIEW

Write to: Professional Recruiting Staff, P.O. Box 7318, San Francisco, CA 94120-7318
Include a resume and college transcripts.

● ENTRY LEVEL OPPORTUNITIES FOR CHEMICAL ENGINEERS ●

BS/MS

	<u>Functional Area</u>	<u>Degree Level</u>	<u>Major Hiring Locations</u>
Facilities Design and Construction Engineering		BS,MS	Throughout the Continental U.S.
	Oil and Gas Production	BS,MS	Throughout the Continental U.S.
	Process Engineering	BS,MS	Throughout the Continental U.S.
	Process Research and Development	MS	Northern California
	Technical Sales / Marketing	BS,MS	Throughout the Continental U.S.

PhD

<u>Fields of Special Interest</u>	<u>Tech Center Locations</u>
Petrochemical and Petroleum Research and Related Activity	Richmond, CA; La Habra, CA Kingwood, TX

An Equal Opportunity Employer

The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested as well as those that are more traditional in nature, which elucidate difficult concepts. Please submit them to Professor James O. Wilkes and Professor T. C. Papanastasiou, ChE Department, University of Michigan, Ann Arbor, MI 48109.

DRAINAGE OF CONICAL TANKS WITH PIPING

JUDE T. SOMMERFELD
Georgia Institute of Technology
Atlanta, GA 30332-0100

Applied mathematics problems in chemical engineering, useful to educators, often appear in various trade journals. Many of these applications have been in the area of fluid dynamics, specifically concerning the time requirements to drain process vessels, which come in a variety of geometrical shapes. Thus, formulas have been summarized [1] to compute the times required to empty vessels of four different shapes: vertical cylinder, cone, horizontal cylinder, and sphere. Later articles gave similar formulas for draining elliptical vessel heads [2] and elliptical saturator troughs [3]. An approximate method for estimating fluid level changes in vertical cylindrical tanks with a multiplicity of outlets (or leaks), of various sizes and at different elevations, has also been presented [4].

All of the above results are based upon the assumption of orifice-type drains, *e.g.*, short tubes, and ignore any associated piping. One article [5] derived a formula for computing the time to drain a vertical cylindrical tank, considering drain piping. Later works [6,7] gave analogous formulas for draining spherical tanks and elliptical dished heads, respectively, with drain piping. Another (not uncom-

mon) shape of process vessel in the chemical industry is conical. Computation of the time required to empty such a vessel through associated drain piping is also amenable to analytical solution, as shown below. A sketch of this configuration is given in Figure 1.

DERIVATION

From the Bernoulli equation, applied to points 1 and 2

$$\frac{P_1}{\rho} + \frac{g_c}{g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho} + \frac{g_c}{g} + \frac{V_2^2}{2g} + Z_2 + h_\ell \quad (1)$$

With the conventional assumptions that $P_1 = P_2$ and $V_1 \approx 0$, we have

$$Z_1 = \frac{V_2^2}{2g} + Z_2 + h_\ell \quad (2)$$

Introducing the Moody friction factor (f) for the drain piping

$$h_\ell = \frac{fL}{d} \cdot \frac{V_2^2}{2g} \quad (3)$$

and noting that $Z_1 - Z_2 = H$, Eq. (2) can be solved for the drain pipe velocity:

$$V_2 = \left[\frac{2gH}{1 + \frac{fL}{d}} \right]^{\frac{1}{2}} \quad (4)$$

A dynamic material balance for the liquid in the tank yields

$$A \frac{dh}{dt} = -aV_2 \quad (5)$$

The cross-sectional area of the liquid level in the tank at any time is merely the circular area described by the radius r at the current level h , or πr^2 .

Jude T. Sommerfeld is a professor in the School of Chemical Engineering at Georgia Tech. He received his BChE from the University of Detroit and his MSE and PhD degrees, also in chemical engineering, from the University of Michigan. His 25 years of industrial and academic experience have been primarily in the area of computer-aided design, and he has published over 100 articles in this and other areas.



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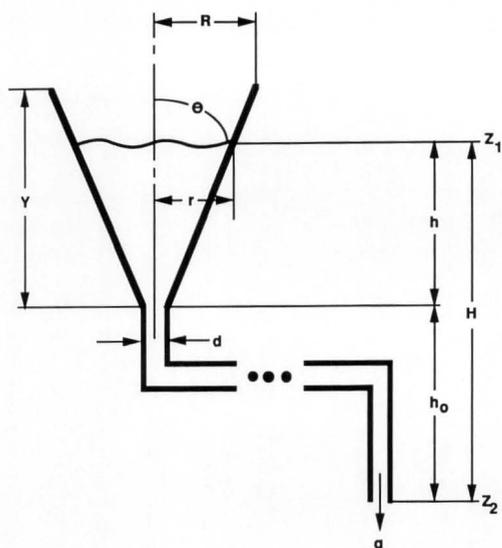


FIGURE 1. Sketch of a conical tank with associated drain piping.

From similar triangles we have

$$\frac{r}{h} = \frac{R}{Y} \equiv \alpha (= \text{TAN } \Theta) \quad (6)$$

and

$$A = \pi \alpha^2 h^2 \quad (7)$$

Recognizing that $a = \pi d^2 / 4$ and after inserting Eqs. (4) and (7) into Eq. (5), we have

$$\alpha^2 h^2 \frac{dh}{dt} = \frac{-d^2}{4} \left[\frac{2gH}{1 + \frac{fL}{d}} \right]^{\frac{1}{2}} \quad (8)$$

Lastly, since

$$h = H - h_o \quad (9)$$

the differential equation to be integrated becomes

$$(H - h_o)^2 \frac{dH}{dt} = - \left(\frac{d}{2\alpha} \right)^2 \left[\frac{2gH}{1 + \frac{fL}{d}} \right]^{\frac{1}{2}} \quad (10)$$

Integrating Eq. (10) from an initial ($t = 0$) liquid level elevation of H_o to some final level, H_f , then yields the following expression for the time required

$$t = C \left[\left(\frac{2}{5} H_o^2 - \frac{4h_o H_o}{3} + 2h_o^2 \right) \sqrt{H_o} - \left(\frac{2}{5} H_f^2 - \frac{4h_o H_f}{3} + 2h_o^2 \right) \sqrt{H_f} \right] \quad (11)$$

where

$$C = \left(\frac{2\alpha}{d} \right)^2 \sqrt{\frac{1}{2g} \left(1 + \frac{fL}{d} \right)} \quad (12)$$

SPECIAL CASES

Two special cases are of interest. The first of these corresponds to complete draining of a partially filled conical tank. In this case, $H_f = h_o$, and Eq. (11) becomes

$$t = C \left[\left(\frac{2H_o^2}{5} - \frac{4h_o H_o}{3} + 2h_o^2 \right) \sqrt{H_o} - \frac{16}{15} h_o^{5/2} \right] \quad (13)$$

The second special case is concerned with complete draining of a completely filled cone. In this case, $H_o = Y + h_o$, $H_f = h_o$, and there results

$$t = \frac{2C}{15} \left[\left(3Y^2 - 4Yh_o + 8h_o^2 \right) \sqrt{Y + h_o} - 8h_o^{5/2} \right] \quad (14)$$

EXAMPLE

A conical tank with a height of 3m and a top diameter of 1.2m is initially filled with water to a level of 2.4m. How long will it take to drain this liquid through a drain pipe system with 150m of equivalent length and with an inside pipe diameter of 1.5cm? The Moody friction factor for this piping system is equal to 0.0185, and the elevation of the outlet from this drain system is one meter below the bottom of the conical tank.

From the problem data

$$H_o = 3.4\text{m}, \quad H_f = h_o = 1.0\text{m},$$

$$\alpha = 0.2, \quad C = 2190 \text{ s/m}^{5/2}$$

Inserting these values into either Eq. (11) or Eq. (13), we find a drainage time requirement of $t = 6108\text{s}$, or 1.70hr.

By way of comparison, from the earlier work [1] the time required to drain the same amount of liquid out of an identical conical tank through a short pipe with the same diameter of 1.5cm, assuming an orifice discharge coefficient equal to 0.80, is 716s.

NOMENCLATURE

A = cross-sectional area of the liquid level in the tank at any time

a = cross-sectional area of the drain piping
 $C = \left(\frac{2\alpha}{d}\right)^2 \left[\frac{1}{2g} \left(1 + \frac{fL}{d}\right)\right]^{1/2}$
 D = upper diameter of the conical tank
 d = inside diameter of the drain piping
 f = Moody friction factor
 g = acceleration due to gravity
 g_c = conversion factor
 H = liquid height above the drain pipe outlet at any time
 h = liquid level in the tank at any time
 h_ℓ = head loss in the piping
 h_o = elevation of the tank bottom above the drain pipe outlet
 L = equivalent length of the piping
 P = pressure
 q = liquid flow rate out of the tank
 R = upper radius of the conical tank
 r = radius of the liquid level at any time
 t = time
 V = liquid velocity
 Y = height of the conical tank
 Z = vertical elevation

Greek Letters

α = R/Y
 Θ = angle formed by the cone with the vertical axis
 π = number pi (3.14159...)
 ρ = liquid density

Subscripts

f = final condition
 o = initial condition
 1 = liquid surface in the tank at any time
 2 = drain pipe outlet

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ChE book review

HAZARDOUS WASTE MANAGEMENT

by Charles A. Wentz

McGraw-Hill Book Company, 1221 Avenue of the Americas, New York 10020; \$46.95 (1989)

Reviewed by

Ralph H. Kummler

Wayne State University

The nation's need for educated and trained professionals in hazardous materials and waste management is enormous and growing [1,2]. In a recent survey paper, my colleagues and I concluded that universities were beginning to respond to the need, albeit slowly [3]. We were able to identify 113 universities offering credit courses related to hazardous waste management (HWM), and 52 universities providing non-credit short courses at the professional level, for a total of 130 universities providing some kind of HWM education. This new area of knowledge is being studied by a very wide array of practitioners,

from traditional chemical and civil engineers and chemists to environmental scientists, environmental health professionals, and medical technologists. It appears that a whole new graduate profession is emerging, since there is plenty of conventional chemical and civil engineering to be accomplished, but the additional role of interdisciplinary management must be implemented. There is a clear need for such new managers at (almost) the entry level, and the career path leads up to the vice-presidential level when environment, health, and safety aspects are combined.

In this context, the pioneering text, *Hazardous Waste Management*, by Charles A. Wentz, fills an enormous need as the first teaching textbook on the market. I expect this book to enable virtually all chemical, civil, and applied science departments to introduce a survey course in HWM. The author is particularly well-qualified to have undertaken this task, having a rare blend of industrial, university

Continued on page 162.

AN OPEN-ENDED PROBLEM IN CHEMICAL REACTION ENGINEERING

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THE HOMEWORK AND examination problems that students encounter in a traditional chemical engineering class typically have unique correct solutions. Such problems certainly provide necessary practice in applying the fundamental course concepts, but if they are used exclusively students might believe, improperly, that all engineering problems are similarly structured. Worse yet, an exclusive diet of well-defined, single-right-answer problems might leave students unprepared for the more open-ended problems they will face in industry or in graduate research. While it is true that students are generally exposed to a measure of open-ended problem solving in the capstone design course, such exposure is comparatively brief and it occurs late in the curriculum.

Recognizing the importance of open-ended problems in engineering and their under-representation in the traditional engineering curriculum, the chemical engineering department at the University of Michigan set a departmental goal of increasing our undergraduates' ability to solve open-ended problems. To achieve this goal we assign at least one open-ended problem in each of our required undergraduate classes. The structure of the open-ended problems is such that they are major, semester-long projects in which students work together in groups of three to five. The open-ended problems offer natural opportunities for

the students to develop problem-solving and life-long learning skills, to think creatively and innovatively, and to exercise engineering judgment.

This paper describes my experience in implementing an open-ended problem in our junior-level chemical reaction engineering class. The problem, which involves evaluating and designing a reactor for destroying organic compounds in an aqueous waste stream, is one that could be easily and profitably used at other universities.

PROBLEM DESCRIPTION

The open-ended problem placed the students in the chemical reaction engineering group of a multinational chemical processing corporation. Their company generated aqueous waste streams that needed to be treated before being discharged into the environment. Incineration was presently being used. On December 7, 1988, the CEO of the company read a short article in the *New York Times* (Figure 1) about an alternative method of treating wastewater streams that involved reacting the organic constituents with oxygen at elevated temperatures and pressures. He wanted to know if this technology, termed wet oxidation, was something his company should be using. After trickling down through a few levels of management, the assignment eventually reached the reaction engineering group (*i.e.*, the students). The groups' stated mission was to evaluate the wet-oxidation technology, make a recommendation about its technical feasibility, and finally, to size a reactor (or process) and specify its operating conditions.

The students received no information other than the scenario above and a copy of the *New York Times* article. There were no restrictions on their use of outside sources of information (*e.g.*, the library, industry, government agencies, personal contacts, *etc.*) so progress down this avenue was limited only by their imagination and initiative. Another available pathway to information was their corporation's Technical Service

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This paper describes my experience in implementing an open-ended problem in our junior-level chemical reaction engineering class. [It] involves evaluating and designing a reactor for destroying organic compounds in an aqueous waste stream, . . . [and] could be easily and profitably used at other universities.

THE NEW YORK TIMES, WEDNESDAY, DECEMBER 7, 1988

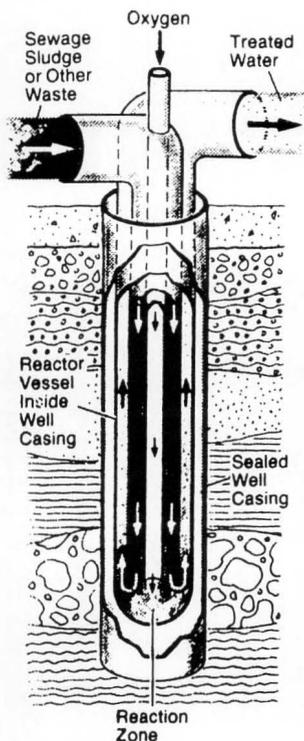
Treating Waste 5,000 Feet Down

If a wet waste material, like sewage sludge, is mixed with oxygen and placed under high pressure, it undergoes a process that chemists call wet oxidation. The sludge, whose disposal is becoming a burden to more and more municipal sewage plants, is converted to relatively clean water and sterile ash.

Such processes, when carried out on the earth's surface, require elaborate vessels under high pressure, special pumps and ample acreage for buildings and equipment. But a Dallas company, the Oxidyne Group Inc., has developed a system that moves the process to the bottom of a well 5,000 feet underground, where it is carried out in a sealed reactor vessel.

In the process, sludge is pumped to the bottom of the well. Because of the weight of the sludge coming down the pipe, pressures at the bottom of the well can exceed 2,000 pounds per square inch. Oxygen is sent down through another pipe and the wet oxidation begins.

Raw sludge is constantly pumped into the system and treated water and ash come out. Wet oxidation produces considerable heat, some of which can be used to drive the process.



SPECIFICATIONS
About 5,000 feet
2,000 psi
550 degrees Fahrenheit

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FIGURE 1

Department. This department would conduct *experimental* work for them, but the students had to define clearly the precise experiments they wanted done and the data they desired to be reported. Additionally, the Technical Services Department conducted experiments only in response to written memos directed to the Technical Services Director.

Note that the scenario described above was not intended to represent the way a real corporation operates. Likewise, the data used in this problem (presented in the next section) were not necessarily intended to mimic those associated with a genuine

hazardous waste problem. Rather, the goal was to develop an open-ended problem in chemical reaction engineering of sufficient complexity to challenge the students without simultaneously overwhelming them.

THE SOLUTION PROCESS

Background Information

The students' initial activity involved gathering information about wet oxidation in general, and the Oxidyne process mentioned in the *New York Times* article in particular. Several groups called or wrote to Oxidyne to learn more about their process technology and its applicability to their particular waste stream. Other groups resorted to the library in search of background information on wet oxidation and vertical, underground wet oxidation reactors. Although the literature provides limited descriptions of underground oxidation reactors [1,2], it is rich in general descriptions of wet oxidation processes [3-8]. Of course, the presence of this information in the literature did not mean that the students, who apparently had little training in performing literature searches, would find it. Indeed, very few groups were adept at locating the relevant papers and patents.

The Search for Data

All of the groups realized that they needed much more data than they initially received in the problem statement. In memos to the Technical Service Director, they requested essential data such as the flow rate, density, temperature, and composition of the aqueous waste stream and the concentrations of the various components. I played the role of the Technical Services Director, but this assignment could also be delegated to a teaching assistant if desired. For this problem, I specified a wastewater stream at ambient temperature flowing at 30 liters/minute. The stream contained 1% each of phenol, chlorophenol, and acetic acid. The precise composition of the stream is, of course, arbitrary, but it is for these three compounds that the literature [5, 9-14] provides the most kinetics data for the wet oxidation reactions. One perceptive group realized that the component concentrations in a real process could exhibit fluctuations even though the process was nominally at a steady state. They sent a memo asking whether such variations occurred and if so, what their magnitude was. To avoid introducing

unnecessary complexity into the problem I told them that the variations in concentration were sufficiently small that they could be safely neglected.

Another piece of information that the students needed was the maximum permissible concentrations of the organics in the reactor effluent. Different groups took different approaches to obtaining this information. Nearly every group did some library research in an attempt to find environmentally acceptable discharge levels for phenol, chlorophenol, and acetic acid. Most groups, however, found an apparent lack of readily available, specific guidelines. Some groups contacted the State of Michigan Department of Natural Resources for state regulations, others contacted the EPA for Federal regulations, still other groups contacted environmental engineers in local industries (*i.e.*, Dow Chemical), and one group contacted the Ann Arbor Waste Water Treatment Plant. Through these and similar efforts the students were able to select reasonable effluent concentrations for the three organic constituents of interest in this problem.

At this point, reaction rate data for the wet oxidation of phenol, chlorophenol, and acetic acid were the only missing pieces of information. Interestingly, only one group recognized that the library was a rich source of reaction rate data, and this group, after a thorough literature search on wet oxidation, was able to obtain sufficient literature data to proceed with the reactor design. In fact, this group was so intent on tracking down all possible literature sources that when they found a reference to a MS thesis on oxidation in supercritical water [14] they contacted the University of California at Berkeley, where the research was conducted, to obtain the author's current address and phone number so that they could consult with him and obtain a copy of his thesis. The members of this group were rewarded for their independence and for realizing that the library, and not the laboratory, is the first place to look for kinetics data.

The other 19 groups relied on the Technical Services Department as their primary source of kinetics data. These groups submitted memos outlining the experimental conditions to be used and the data to be taken. With very few exceptions, the groups' first attempts at identifying conditions that would produce useful rate data were unsuccessful. They typically selected initial reactant concentrations that were too high to allow for isothermal operation of a laboratory reactor (the wet-oxidation reaction is very exothermic) or combinations of temperature and residence time that led to very high conversions at very short times (oxidation reactions are very rapid at elevated temperatures). An additional problem that some

groups encountered was that they requested data that were not as useful as they had envisioned. For example, one group requested that the Technical Services Department run a wet oxidation reaction in an isothermal CSTR, sample the liquid phase at specified times, and identify and determine the concentrations of the different components. They were planning to use the concentration vs. time data to derive the reaction rate laws. Of course, concentrations do not change with time in a steady-state CSTR; thus the reply memo from the Technical Services Director showed that the component concentrations in the effluent stream, though lower than those in the feed stream, remained time invariant. Upon examining the reply memo, the group eventually realized its mistake. The next memo requested experiments in a batch reactor wherein concentrations do change with time.

The groups' requests for reaction rate data, expectedly, covered a wide range of temperatures, pressures, and initial concentrations. To accommodate each request precisely would have been impossible without extensive laboratory work. Thus, when a group identified experimental conditions that could lead to the acquisition of useful kinetics data, my reply memo consisted of a handout containing much of the literature data available for the wet oxidation of phenol [5, 9-12], chlorophenol [5, 11-13], and acetic acid [14], the three compounds of interest in this problem. The experimental conditions under which these data were taken covered temperatures from 185 to 445° C, pressures from 54 to 240 atm, and initial reactant concentrations from about 50 to 12,000 ppm. It included data obtained from both batch and plug-flow laboratory reactors.

Because the data given to the students were real experimental data taken directly from the literature, they reflected experimental uncertainties, and they contained occasional bad points. Furthermore, because I used different data sets taken by different investigators under different experimental conditions and interpreted using different assumptions, the collection of data given to the students was not entirely internally consistent. Thus, in interpreting their kinetics data and deriving reaction rate laws, the students had to exercise judgment and decide which data sets were the most reliable for their design calculations.

Reactor Configurations and Operating Conditions

Having obtained all the necessary flow rates, compositions, and kinetics data, the students next began to consider the issues involved in selecting and designing a wet-oxidation reactor. Because the *New York Times* article described a vertical oxidation reactor

that descends 5,000 feet below the surface of the earth, all of the student groups took this reactor configuration as their starting point. Most groups began trying to model such a reactor using a combination of ideal reactors. Several groups contacted Oxidyne for more information about their reactor systems and for assistance in their modeling efforts. These initial modeling activities revealed that the students perceived their assignment to be sizing a vertical, underground oxidation reactor. By unnecessarily confining themselves to a specific reactor configuration so early in the solution process, however, they failed to see the broader issues involved in the problem. Therefore, I spent a few minutes of class time encouraging them to think about the real problem (which was not necessarily the same as the stated problem) in which the CEO was interested. After some discussion along these lines the students began to realize that the real problem was not simply to size an underground oxidation reactor, but rather for their company to make its products without experiencing any adverse environmental consequences. Upon identifying the real problem, many groups began to develop ideas such as modifying the manufacturing process to minimize the amount of waste produced, developing new technologies that generated less or more easily treated wastes, separating and recovering the components in the waste stream, and exploring alternate means of wastewater treatment (*e.g.*, ozonation, biodegradation, and the use of catalysts). Not all groups explored all these themes, of course, but all of them did at least broaden their scope from the initially narrow one that considered only the underground reactor.

After examining several alternative solutions to the real problem, many groups concluded that because the wastewater stream flow rate was low, and because it was relatively dilute there were no real advantages in using an underground reactor. These groups then proceeded to design a conventional above-ground reactor suitable for wet oxidation. They used either a PFR or a CSTR as the basis for their design calculations.

The majority of the groups, however, decided that an underground oxidation reactor remained as the best possible solution. These groups sent memos to the Technical Services Director requesting, among other things, the location of the chemical plant that generated the wastes, the composition of the earth's crust at the plant site, the thermal diffusivity of the ground, and the population density around the site. I tried to keep the problem general and also minimize the amount of data I had to manufacture by replying

that because the corporation was multinational it sought a technology that could be implemented anywhere in the inhabited world.

Most groups demonstrated a reluctance to deviate from the operating conditions of 2000 psi and 550°F (288°C) noted in the *New York Times* article, and their final designs typically specified conditions near those. Although the students realized that reaction rates increased with temperature, they seemed quite hesitant to specify higher reactor temperatures. Interestingly, a few groups thought that the critical temperature of water, which is 374°C, posed some sort of thermodynamic barrier that dare not be crossed during the reaction. These groups carefully designed their reactors so as not to exceed this critical temperature.

After some discussion . . . the students began to realize that the real problem was not simply to size an underground oxidation reactor, but rather for their company to make its products without experiencing any adverse environmental consequences.

The origin of this mistaken impression is unclear, especially considering that the students were given experimental rate data taken at supercritical conditions [13,14]. Several groups, fortunately, realized that the critical temperature was not a barrier, and they selected high temperatures that led to high reaction rates. These groups, through reading the literature [1,13-17], came to appreciate the unique advantages that supercritical operation offers.

SUMMARY OF STUDENT SOLUTIONS

The fact that the assigned problem was truly open-ended in the sense that multiple solutions existed was verified by the diversity in final designs. Of the twenty groups working on the problem, eleven selected underground oxidation reactors such as the one described in the *New York Times* article. Eight groups decided that the underground reactor afforded few advantages for this particular application, and they selected a more conventional above-ground flow reactor (*e.g.*, PFR or CSTR). One group apparently found the decision of reactor placement a difficult one, so these students designed a reactor that they claimed could be operated either horizontally above the ground or vertically underground to meet the plant manager's preference. It is interesting to note that the majority of the groups retained the vertical, underground design and the operating conditions highlighted in the brief *New York Times* article. I think it is unlikely that any of these groups would have recom-

mended such a reactor configuration had they not first read the newspaper clipping. Thus, in this case, the final solution tended to reflect the initial information given to the students.

The final reactor designs also exhibited tremendous variety in their mode of operation (*e.g.*, isothermal, adiabatic, and non-adiabatic reactors with heat transfer were all recommended) and operating temperatures (170 - 727°C). The calculated reactor volumes varied by six orders of magnitude as the smallest reactor volume was 0.845 liters (roughly the size of a pop bottle) and the largest was 494,000 liters (roughly the size of three large railroad tank cars). The fact that different groups arrived at very different final designs can be attributed primarily to the different interpretations of the experimental kinetics data, the different operating conditions and reactors selected, and the different effluent concentrations deemed to be acceptable.

SKILLS USED AND DEVELOPED

This open-ended problem gave the students an opportunity to use and develop several different types of skills. Indeed, a thorough solution to the problem required the students to exercise their technical, problem-solving, and communication skills.

• **Technical Skills** *Technical skills were developed via the students' application of some of the key concepts of chemical reaction engineering. Topics such as modeling ideal reactors, obtaining and analyzing experimental rate data, performing energy balances for an exothermic reaction, handling situations with multiple reactions, and dealing with transport effects in gas-liquid reaction systems were all components of the open-ended problem solution. Several of the groups also wrote computer programs to solve the simultaneous mole and energy balances that arise in this design problem.*

• **Problem-Solving Skills** *In addition to practicing the application of course-specific technical topics, the students also exercised more generic problem-solving skills. For example, they gained an appreciation for the importance of problem identification and definition. The exercise in distinguishing between the real problem and the apparent problem, which incidentally is unique to open-ended problems, helped the students to generate alternative solutions to the one initially identified by the CEO. This open-ended problem also forced the students to adopt and develop a problem solving strategy. They had to identify the important issues involved in the problem, plan a means of addressing those issues, and plan an experimental program (or literature search) for obtaining the required data. The problem also allowed the students to be creative, innovative, and resourceful. Most of the students enjoyed this aspect of the problem for they rarely have this freedom when solving more traditional homework exercises. Furthermore, through this open-ended problem, the students gained an appreciation for the issues involved in solving a complex problem. They realized that a completely rigorous approach to the design of a wet-*

oxidation reactor for a multicomponent mixture was beyond their level of knowledge and beyond the scope of the course. Thus, the students had to decide where they could make assumptions that would simplify the problem without seriously compromising the final solution. Not all groups were equally adept at this task, however, and several groups seemed perfectly comfortable making assumptions that simplified the problem but did not reflect reality. One final skill that this problem afforded the students was the opportunity to sharpen their engineering judgement. The groups had to decide what type of reactor to use, what operating conditions to select, whether or not to use an underground reactor, and how to analyze their ambiguous reaction rate data.

• **Communication Skills** *The structure of this semester-long open-ended problem was such that it included a large amount, and different types, of writing. For instance, the students wrote one-page memos to the Technical Services Director when they needed experimental data. They also submitted a two-page (maximum) progress report around the middle of the semester, and then a comprehensive final report at the end of the semester. This emphasis on technical writing was intentional. In fact, portions of two different class lectures were devoted to a discussion of the key elements of good technical writing, and the students also had an in-class exercise wherein they revised a poorly written paragraph taken from one of their peers progress reports. To provide the students with an additional resource, I also used The Elements of Style by Strunk and White as a required text for the course.*

*I encouraged the students to write each memo and report thoughtfully by returning for revision any written document that contained more than three grammatical or stylistic errors (*e.g.*, sentence fragments, lack of subject-verb agreement, excessive use of passive voice, etc.). As expected, revisions were frequent early in the semester. I wanted the students to learn from their mistakes, however, and not necessarily be punished for them. Therefore, revising a memo did not affect the student's grade, but merely delayed their receipt of experimental results from the Technical Services Department. A revision of the progress report likewise carried no penalty other than the extra work associated with turning in the report a second time. Revision of the final report, however, did lead to a ten percent reduction in the group's score for the project. Only four of the twenty groups had to revise their final reports, however, and even those four reports showed signs of having been written carefully and thoughtfully.*

SUMMARY AND RECOMMENDATIONS

The open-ended problem described in this paper provided a good opportunity for the students to apply key elements of chemical reaction engineering in addition to developing more generic problem solving skills and communication skills. Most of the students enjoyed the problem and the departure it presented from the more conventional homework exercises.

One point that resonated from the student evaluations at the end of the semester was that the course, as a whole, involved too much work. I recognized that this open-ended problem would require a significant effort from the students, so I covered one less chapter

in the text than I had previously covered in the course. Apparently, however, the omission of this one chapter did not compensate for the addition of the open-ended problem. Therefore, care must be taken to ensure that the incorporation of a major open-ended problem is accompanied by the reduction of other assignments so that the students are not overloaded. Fortunately, the open-ended problem described in this paper is sufficiently flexible that it can be modified to suit an instructor's preferences and the time available in the course. For instance, the amount of student effort required can be reduced by providing literature data [5, 9-14] for the kinetics, specifying the desired concentration of organics in the effluent, or specifying a single organic pollutant in the wastewater stream rather than a multi-component mixture.

ACKNOWLEDGEMENTS

H. Scott Fogler initiated the departmental effort to incorporate open-ended problems in the curriculum, and Brice Carnahan originally identified the *New York Times* article referenced in this paper as the basis for a problem in reaction engineering. Tom Thornton performed the literature search and obtained the kinetics data used in this open-ended problem.

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ChE book review

POLYMER CHEMISTRY: AN INTRODUCTION

(Second Edition)

Raymond B. Seymour and Charles E. Carraher, Jr.
Marcel Dekker, Inc., New York, 10016
720 pages, \$45.00 (1988)

Reviewed by
William J. Koros
The University of Texas

This book is an updated version of a text which was first published some years ago by McGraw-Hill. This second edition comprises the eleventh volume in a series of undergraduate texts dealing with a broad range of topics in chemistry. As is pointed out in the forward to the book, written by Herman Mark, this new edition is quite up-to-date in terms of topical coverage, but without unnecessary complications. The book is easily read and has an almost conversational tone to it. One can imagine sitting across from the two authors (whose broad knowledge of polymer science is well-known) and having the book unfold in a casual, but still logical, fashion.

The revised text includes a number of new topics, and the authors note that the book meets the ACS guidelines for topical coverage in an introductory polymer chemistry course. A glossary and series of questions related to the material is given at the end of each chapter. The questions at the end of the chapter are a plus for the book since it is difficult to obtain good homework exercises in the polymer field without actually synthesizing them oneself. Nevertheless, while these exercises are useful, they are mostly discussable in nature and do not satisfy the persistent need for a really good compilation of computational problems to illustrate principles discussed in a polymer text.

As must be the case whenever one considers a wide range of topics and is committed to keeping the page-count within bounds, none of the topics is treated in any detail. The title, *Polymer Chemistry*, is not

Continued on page 167.

COMPOSITE MATERIALS

An Educational Need

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CHEMICAL ENGINEERING is a dynamic discipline. However, the petroleum and traditional chemical industries are no longer expanding and the result is dwindling employment opportunities for chemical engineers. Although chemical engineers will continue to play a major role in these industries, the future of chemical engineering can and should be enhanced by identifying new areas in which students can be appropriately trained. This would be mutually beneficial to both students and industry since it would not only expand the employment horizon for students but would also supply industry with engineers for new technologies.

Several emerging technologies (including biochemical/biomedical engineering, microcomputer applications, process control and safety, synfuels, and advanced materials) have been identified as natural extensions to traditional chemical engineering [1,2]. This paper deals mainly with incorporating the concepts and applications of advanced composite materials into existing chemical engineering programs. Ideally, the chemical engineering curricula should have at least four electives which allow a concentration in one of the emerging technologies listed above [3]. However, due to general education requirements and/or other constraints, chemical engineering programs do not allow much flexibility for the selection of technical electives. The solution proposed here would expose students to various areas of composite materials, and that, in turn, would expand their employment opportunities to the aerospace and automotive industries.

This paper deals mainly with incorporating the concepts and applications of advanced composite materials into existing chemical engineering programs.

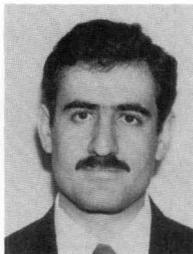
BACKGROUND

Composite materials consist of reinforcing particulates or fibers such as glass, graphite, metals, or ceramics in a matrix that can be polymeric, metallic, or ceramic. The type and composition of the constituents and the processing procedure can be varied in order to tailor the composite properties. These properties, which are superior to those of the individual constituents, include a high strength-to-density ratio, a high stiffness-to-density ratio, high or low conductivity, and resistance to corrosion, fatigue, and stress rupture.

The industrial applications of composite materials span a wide range from advanced satellites to the simple golf club. Applications include aircraft components such as wings, helicopter blades, satellites, missiles, and engine components. In the automotive industry, body panels, brackets, drive shafts, and springs are made of composites. The consumer industry uses composites in boats and in sporting goods such as racquets, golf clubs, and fishing rods.

The processing methods vary depending on the type of reinforcement and matrix. For thermoplastic materials, the techniques include injection molding, compression molding, and cold stamping. Thermoset processing may employ contact molding, matched die molding, reaction injection molding, pultrusion, filament winding, or vacuum bag autoclave molding.

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JUSTIFICATION

There is a critical need for personnel with some training in the design and processing of composite materials. The current demand is estimated at eight hundred engineers while the supply is only eighty to one hundred fifty [4,5]. The composite industry is believed to be growing at an annual rate of twenty percent [4]. A U.S. Office of Technology Assessment report indicated that 22 million pounds of advanced composites were produced worldwide in 1984 and estimated that the production would increase to 200 million pounds by year 2000 [4]. Most composite education is obtained in graduate schools, with most of the graduates working in research and development. Newly graduated BS engineers are still needed for design and development, manufacturing, and technical sales (where forty percent of the available jobs are) [6].

One undergraduate program in composite materials engineering has been started at Winona State University. However, this one program cannot meet the demand in view of the tremendous growth of the composite materials industry (raw materials usage by the composite industry is projected to grow to \$10 billion by 1992 [4]). Only a few other schools have started similar programs, and most other programs have curricula with only one, or no, technical electives. An alternative approach would be to incorporate the various concepts into existing classes with example problems, lecture materials, and/or class projects.

CONTRIBUTIONS AREAS

Several traditional chemical engineering principles are essential in the composite materials industry. The processing of composites consists of applying heat and pressure. The heat is needed to initiate chemical or physical changes, and the pressure is needed to compact the product to its final shape. Heat transfer theories are needed to understand and to design the various processes. Fluid flow theory is needed to pre-

TABLE 1
First Chemical Engineering Introductory Class

1. Introduction to Composite Materials
 - A. Definition
 - B. Classes of composites
 - C. Industrial applications
 - D. Why composites
 - E. Specific properties
 - F. Brief history
 2. Constituent Materials
 - A. Fibers / Reinforcements
 - B. Matrix Materials
-

dict resin flow, which thus predicts suitable processing parameters and results in appropriate fiber and resin content and distribution. Mass transfer concepts are necessary to study environmental effects of moisture and solvents during the composite part as well as to manage void formation and growth during the manufacturing process. Chemical kinetics information is required to follow the chemical reactions in thermosets and crystallization in thermoplastics as well as to determine the heat generation rate. Traditional process design principles can be applied to product, process, and plant design. Many chemical engineering concepts are used in composite materials engineering. Our proposal is to introduce the students to examples depicting the application of basic engineering concepts to composite materials and to encourage the students to become familiar with the terminology, thus providing them with a starting point for further learning.

IMPLEMENTATION

The application of chemical engineering principles to composite materials design and manufacturing can be included in several traditional chemical engineering classes. As shown in Table 1, a brief introduction to the role materials play in a typical chemical engineering assignment, followed by an introduction to composite materials, can be covered in an introductory class in chemical engineering.

The concepts outlined in Table 2 can be introduced

TABLE 2
Transport Phenomena

- I. **Fluid Mechanics**
 1. Resin Flow During Autoclave Cure
 - A. Flow between parallel plates (University of Michigan Model)
 - B. Flow around plates and cylinders (McDonnell Douglas)
 - C. Flow through porous media (University of Dayton, MIT)
 - D. Resin loss, compaction rate, and fiber volume fraction
 2. Other Processes
 - A. Pultrusion
 - B. Extrusion
 - II. **Heat Transfer**
 1. Thermophysical Properties of Anisotropic Systems
 - A. Resistance analogy
 - B. Volume average
 - C. Empirical formula
 - D. Transport properties
 2. Heat Transfer Codes
 - A. Modeling heat transfer in an autoclave (convective BC)
 - B. Heat transfer in a press (temperature and heat flux BC)
 - C. Heat generation term due to exothermic chemical reactions
 - D. Coupled heat transfer and fluid flow in an extruder
 - III. **Mass Transfer**
 1. Diffusion of Water/Solvents in Composites
 2. Void Nucleation and Growth
-

in fluid mechanics, heat and mass transfer, or an equivalent transport phenomena class. The basic principles are still the same; the applications are different. The topics cover modeling of the transport processes and the determination of various composite thermophysical and dimensional properties. In a transport phenomena laboratory, measurement of composite materials transport properties can be implemented as shown in Table 3. Other experiments for temperature and pressure measurements can also be incorporated.

The basic concepts pertaining to polymerization and crystallization kinetics described in Table 4 can be covered in a kinetics or a reactor design class. These topics deal with reaction mechanisms as well as the introduction of nucleation and growth rate effects on the crystallization kinetics.

The composite manufacturing techniques listed in Table 5 can be introduced in a unit operations class and/or laboratory. Studying the effect of the various process parameters on the properties of the final product can help students become familiar with the unit operation itself and manufacturing aspect of composite materials.

TABLE 3
Transport Phenomena Laboratory

In this laboratory, experiments related to composite materials can be developed and used. These could include:

- Measurement of temperature distributions during the cure of a composite material and comparison with predicted temperatures from heat transfer calculations.
- Estimation of the diffusion coefficient of moisture in composite using percent weight gain measurements and available diffusion codes. (This experiment will require several weeks.)
- Viscosity measurement during the cure of composite materials using rheometrics, dielectric monitoring or acoustic attenuation techniques.
- Measurement of the apparent thermal conductivity of composite materials using temperature and heat flow measurements.

TABLE 4
Kinetics and Reactor Design

1. Polymer Kinetics
 - A. Polycondensation reactions
 - B. Free radical addition polymerization
 - C. Non-radical addition polymerization
 - D. Copolymerization
 - E. Available kinetic models
 2. Crystallization Kinetics
 - A. Avrami equation
 - B. Avrami equation-based polymer crystallization models
-

Perhaps the most flexible area for the introduction of composite materials applications is in the design area. Most universities have two design classes. The first design class, covering an overview of general design considerations and the use of economic factors and optimization as applied to traditional chemical engineering design problems, can remain unchanged. The second design class can be modified to introduce product and process design requirements as applied to composite materials and to implement a composite segment with applications in the aerospace, automotive, and consumer industries. A design class is an ideal place for a class project that incorporates and summarizes the concepts learned in the first three years. The project could consist of choosing a specific novel application for an advanced composite. The product requirements for the specific application, as well as the manufacturing process, could then be iden-

TABLE 5
Unit Operations

Unit operations used in composite materials manufacturing include:

1. Filament Winding
 2. Prepreg Layup
 3. Autoclave Molding
 4. Injection Molding
 5. Compression Molding
-

TABLE 6
Product and Process Design

1. **Process Modeling and Optimization**
 2. **Material Selection Criteria**
 - A. Geometric considerations
 - B. Properties requirements
 - C. Cosmetic requirements
 - D. Processability/maintainability
 - E. Product quality
 - F. Cost
 3. **Design Concepts**
 - A. Cost of design and manufacturing
 - B. Coordination between design, tooling, and manufacturing
 - C. Product quality assessment and control
 - D. Mathematical analysis
 - E. Joint design
 - F. Design databases
 - G. Computer programs for design (LAMRANK, CLASSIC)
 - H. Life-cycle analysis
 4. **Project**
 - A. Justification for using composite materials
 - B. Constituent materials selection
 - C. Manufacturing techniques chosen
 - D. Meeting design requirements
 - E. Quality assurance
 - F. Modifications and recommendations
-

tified [7,8]. The concepts covered in this class and the project outline are listed in Table 6.

Finally, a seminar can be used to invite chemical engineers from the composite industries to share their experiences and to introduce the students to various composite industry problems and solutions.

FINAL THOUGHTS

Both the mechanical behavior of composite materials and the effect of processing parameters on the mechanical properties are important areas of composite materials manufacturing and design. Although the mechanics of composites topics are more appropriate in a mechanical engineering curriculum, chemical engineering students might choose to take a strength of materials class where the concepts of anisotropy and mechanical behavior are introduced.

Despite the importance of composite materials and the essential need for engineers knowledgeable in this emerging technology, introducing composite materials topics into the existing curricula should be done without compromising the basic engineering sciences. The principles currently covered should remain intact, but the examples and the application of these principles could be tailored to composite materials.

In order to implement the plan, the department should have faculty members working in the area of composite materials who can bring their experience and expertise to the classroom (our department has five faculty members who work in the polymer/composite materials area). A department looking for a new direction, but without expertise in the field, could retrain faculty who have an interest in this area through short courses, conferences, and industry/government faculty summer internships. Another mechanism for implementation could be through the use of part-time faculty who have extensive experience in the composite materials industry.

CONCLUSIONS

A strategy for introducing composite materials concepts into existing classes has been proposed. Implementing the application of basic chemical engineering principles to composite materials is necessary if we are to meet the demand for chemical engineers knowledgeable in this emerging technology. It is an alternative that can be used in schools where concentrations in the areas of new technologies cannot be introduced. Finally, this approach will not require re-accreditation since classes and the basic principles remain the same; only the examples and the applications would change.

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INTRODUCING APPLICATIONS OF BIOTECHNOLOGY TO HIGH SCHOOL STUDENTS

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IT INCREASINGLY APPEARS that high school students who have the opportunity to take science and mathematics courses which lead to careers in technology fail to do so. This national dilemma may stem, in part, from the fact that students simply have no idea of the socially positive nature of technological contributions. Those students who avoid taking the most challenging mathematics and science courses while in high school may not know how exciting the practical results of their knowledge can be, or how useful their contributions could be. Briefly, high school students need to be given a more pragmatic grasp and understanding of technology in addition to guidance concerning their career paths. With some practical understanding of technology, these same students might then pursue advanced science and math courses while in high school.

EXPLORATORY PROGRAM

We have been investigating ways to introduce applications of modern biotechnology to high school students, with the objective of incorporating these applications into high school science courses. To date we have carried out two quarters of a pilot program, meeting after school with local ninth and tenth graders. The sessions in the first quarter were one hour long and were of a "show and tell" nature. (About twenty-five students began this first group and about twenty completed the quarter). For the second quarter, we held two-hour sessions in which we introduced a topic and then conducted a demonstration which included some measurement. This was followed by an "experiment" conducted with groups of three to four students. In all cases, the sessions closed with a writ-

ten quiz and a discussion of the results of the quiz.

This second-quarter pilot program involved two groups of students, and fifty-two out of sixty-four students completed the program and received a certificate. Moreover, fifteen of the students volunteered to continue with a summer internship project. We now believe it is important to also work closely with the teachers and are planning a summer session for high school science teachers.

Our objective in conducting this exploratory project was to learn how to introduce technology into high schools. Biotechnology was selected as our theme because of the background of several of our engineering faculty in this field, and because this technology has recently attracted media attention and, we as-



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sumed, student interest. Moreover, biotechnology cuts across essentially all standard career fields and is most often interdisciplinary in practical implementation.

PROGRAM INITIATION

The first quarter of the pilot program was initiated through an established program at Northeastern University which provides academic support to, primarily, minority students. This first quarter of our "Applications of Biotechnology" program was offered to tenth graders, and our one-hour session on the topic was followed by one hour of mathematics for the same students. Our retention through the quarter of about twenty students out of the beginning twenty-five was exceptional when compared to other attempts to present topical issues to high school students.

Our pilot program for the second quarter was initiated when two professors visited a biology teacher and one of his ninth grade classes at a local high school. After discussing our plans for a second after-school pilot course, the biology teacher (with the approval of his Headmaster) agreed to hand out an application form and questionnaire. We had hoped to have as many as fifteen students enroll but had anticipated perhaps twelve. We were all surprised when sixty-four students applied. The biology teacher and others at the school tried to, but could not, pinpoint the "key" words in the application that attracted the interest of so many students.

At this point, because of the large number of applicants, the Headmaster wanted to know what our criteria would be for accepting the planned-for 12-15 students and rejecting the others. We then decided to accept all of the applicants and to divide our second pilot project into two classes to accommodate them. Each class would have identical presentations and would meet after school for two hours on Monday and Tuesday.

CONDUCTING A SESSION

Our plan was to present approximately a one-hour informal lecture on a topical subject, with as much question-and-answer participation as possible. While some of the classroom discussions also included show-and-tell demonstrations, most of this first portion of the two-hour session was used to introduce the technical topic of the day. As noted previously, we prepared a typed quiz for the students to take. To save time, the snack-break was coupled with the written quiz, enabling an immediate review of the quiz. The second portion of the session was then devoted to some type

. . . high school students need to be given a more pragmatic grasp and understanding of technology in addition to guidance concerning their career paths.

of "hands-on" experimental work which involved some aspect of quantitative measurement.

A discussion of one particular session will be useful here. In the session on pharmaceuticals, we demonstrated "pan agglomeration" or "prilling" of "tiny time capsules" to the class in the first portion of the session. In the second portion, students were divided into groups of three students each, and each group was given three pairs of pre-pressed tablets, *i.e.*, six tablets, along with a beaker of water. The tablets contained sodium bicarbonate and citric acid, so the reaction, when dropped into water, was a visible effervescent carbon dioxide. It surprised the students to learn that the tablets had been prepared under 2,000, 4,000, and 6,000 p.s.i. compression, and therefore they had significantly different "release" times.

After measuring the timed release of these tablets, we passed out similar tablets, but with a biopolymer coating (also demonstrated by spray coating), to demonstrate a long-acting, or "controlled release," system. As expected, these time-capsules had a much longer "lifetime."

TOPICS

A list of the topics covered in each session during our pilot program follows.

• Session 1 •

Bioconversion of Municipal Solid Waste

In this session we discussed the bioconversion of municipal solid waste. Under appropriate conditions certain microorganisms degrade wastes and produce fuel gas, a valuable by-product. The magnitude of the problem of disposing of municipal solid waste was reviewed using 35mm slides of "dump sites" in different places throughout the world. Students seemed impressed that substitute natural gas, used in some of their own homes, could be produced from wastes—through the action of microorganisms.

• Session 2 •

Medical Applications of Plastics

In this session we discussed medical applications of biopolymers. Biopolymers are special plastics that are used, for example, as surgical staples, bone

“grout” (a putty-like material used for bone repair), heart valves, bone splints, *etc.* We focused, in particular, on biodegradable plastics used as implantable long-acting controlled release drug delivery systems. For this application, a conventional drug (for example, an antimalarial drug) is blended with a biodegradable plastic. This drug/polymer matrix is then extruded into a small thin rod, about the size of a pencil lead. When this rod is implanted, the drug slowly diffuses out and, as the polymer biodegrades, a continuous release of drug occurs, providing protection (in this example case) against malaria. We used 35mm slides to illustrate a number of controlled release drug delivery systems in model animal situations.

• Session 3 •

Biopolymers in Concrete

The purpose of this session was to introduce a novel application of biopolymers, *i.e.*, using a biopolymer in concrete with the objective of reducing water permeability. The reasoning was that using a water soluble plastic in making concrete would reduce water penetration, resulting in an improved material for pothole repair. Students, in groups of three, carried out the preparation of concrete in the laboratory. Samples were prepared with and without biopolymer. Using similar samples of concrete (prepared earlier for this class), students observed and recorded compression strength testing on the Instron tester. Most students were not aware of the technology involved in considering an improved concrete.

• Session 4 •

Production of Bread Yeast

Technology for producing yeast used in making bread is similar to the technology for producing antibiotics and other pharmaceuticals and biologicals. Using bakers yeast as a model, students carried out the initial plating of the yeast (many came back the following week to show their cultures), and they observed the yeast growing in shake flasks and the production of yeast in a pilot-plant fermenter. To stress the importance of being able to measure key parameters, samples of yeast in the active growth phase were taken, and students monitored the oxygen uptake rates. The students showed an interest in actually observing microorganism-growing situations.

• Session 5 •

Prevention of Acid Rain

“Acid rain” is generally believed to be caused by burning coal which contains substantial amounts of

sulfur. Research work is under way to use enzymes to clean the organic sulfur from coal. We presented a demonstration of enzyme activity as well as measurement of sulfur removal. The students recognize the importance of reducing acid rain and were impressed by the catalytic activity of enzymes.

• Session 6 •

Preparing Pharmaceutical “Tiny Time Capsules”

The technology of pan agglomeration, or “prilling,” was demonstrated, showing how “tiny time capsules” are produced from a mixture of powdered pharmaceutical chemicals. Components of commercial Alka Seltzer® (citric acid and sodium bicarbonate) were used as a model system. After “prilling,” the small beads were coated or encapsulated with biopolymer, thus providing for a longer-acting release of the active ingredients. Prior to the class we had also prepared (by compression) tablets of citric acid and sodium bicarbonate, and each student group of three received three tablets. After placing a tablet into a beaker of water, the group would determine the time required for complete dissolution. Since we had prepared the tablets under different pressures (2000, 4000, and 6000 psi), the time for dissolution varied. The tablets coated with a polymer were found to have much longer lifetimes. The students were interested in observing and learning how selected conventional pharmaceuticals are produced.

• Session 7 •

Field Trip to Sewage Treatment Plant

We took a field trip to the Massachusetts Water Resources Authority sewage treatment plant located on Deer Island. Plans for the new Boston harbor cleanup, to be carried out from this facility, were also reviewed. The tour was directed by a person intimately familiar with all operations of the plant and it involved site visits to all major aspects of the facility. Students were impressed with the size of both the treatment plant and the new composting pilot plant (for converting sewage sludge residuals into a material for organic gardening).

• Session 8 •

Food Technology Applications

Three undergraduate chemical engineering students presented brief overviews of their special assignment dealing with food technology. One student presented the procedures for concentrating orange juice, the central step of which is freeze crystallization. Comparisons were made between preparing

concentrated orange juice (freezing from water) and shipping "not from concentrate." Another student considered freeze drying of meat such as that used in making certain soup mixes. There was a lively discussion about food preservation techniques, including the use of chemical preservatives and methods used in other countries.

• Session 9 •
Unit Operations

In this session, the students were introduced to process systems and "scale-up," *i.e.*, the consideration of how chemical and biochemical products are manufactured on a larger, more practical scale. Unit operations consist of singular processing units which, when combined, make up essentially all chemical/biochemical production plants. The classroom discussion stressed the importance of measurements of fluid flow, temperature, *etc.* The laboratory experiment, using a completely computer-controlled humidification unit, involved groups of students monitoring changes in input variables and subsequent changes in the system output.

• Session 10 •
"CMA" Deicing Salt

Calcium magnesium acetate, or "CMA," is a non-corrosion, non-polluting organic deicing salt (developed under sponsorship of the Federal Highway Administration) that is produced from dolomitic limestone and acetic acid. In this session we first reviewed how microorganisms may be used to directly produce many organic chemicals (lactic acid, ethanol, methane/carbon dioxide, acetic acid, *etc.*). Using CMA as an example, we discussed how further processing of the fermentation product (acetic acid, in this case) may be required. Following an overall description of the conversion of organic wastes to CMA, liquid-liquid extraction of acetic acid from fermenter broth was demonstrated in the classroom. Then each group of three students received a sample of the extracted acetic acid along with some powdered calcium carbonate. Students were able to observe the formation of product calcium acetate. We concluded by discussing the advantages and disadvantages of both sodium chloride and CMA as road salts. Students appeared unanimous that reducing the cost of CMA was the most effective way to achieve wide acceptance.

• Session 11 •
"Focused" Microwave Applications

It is not often that you can bring together a strik-

ing example of both chemical and electrical engineering, but we did this in our session on "focused" microwave applications. Specifically, we addressed the problem of non-invasive cancer treatment, as well as microwave sterilization. This topic was presented by giving an overview of the technology, and following up with a demonstration. The technology of cancer treatment by microwaves centers on the fact that cancer cells have high electrical conductivity and are more sensitive to temperature increase than normal tissue. Thus, techniques for focusing, or directing, the microwaves enables heating of the cancer cells to the point of cell death, without serious damage to adjacent normal cells. We demonstrated this technique (using a home microwave oven) by first showing that different fluids (salt water, tap water, ethanol, salad oil, aqueous solutions of the water soluble polymer polyvinylalcohol) have different electrical conductivities. We then placed a small beaker of one fluid (saline, modeling a tumor) in a larger flat tray containing another fluid (salad oil, with much lower conductivity). We saw how the fluid in the beaker could be elevated to a temperature substantially higher than the one in the flat tray. We also explored how an air-foamed material (whipped cream) absorbs microwaves, comparing that to beakers of selected fluids placed in the foam.

• Session 12 •
Organ Transplants

One of the leading researchers on immunosuppression for organ transplants gave an overview of this topic, pointing out both the problems and the progress in this area. We discussed the concepts of organ acceptance and rejection between donor and recipient. A number of 35mm slides were used to illustrate, for example, both healthy kidneys and those that had been rejected. Because it is illegal to demonstrate examples on live animals to high school students, we could not illustrate the standard "skin patch" test. However, we did take the students to the university research operating room and showed them mice at various stages of skin patch testing.

• Session 13 •
Genetic Engineering and Production of Seaweeds

This session addressed the many uses of seaweeds and the need for genetic engineering of new seaweed strains. In addition to describing the objectives and the methodology behind genetic engineering technology in general, the global perspective of growing and harvesting seaweeds (especially in developing coun-

tries) was presented. We demonstrated the "thickening" characteristics of agar and presented examples of edible seaweed products. The session concluded with a tour of the laboratory in which seaweeds are cultured and grown.

EVALUATION OF THE SESSIONS

Unfortunately, we did not survey the students before or after conducting our first pilot quarter. However, we did so for the second quarter. As noted above, an application/questionnaire was given at the initiation/conclusion of these sessions. Some overall observations follow.

First, on the original application, only six students indicated a serious interest in pursuing a career in science or engineering (no one mentioned the word "engineering"). On the concluding questionnaire, only six students did *not* indicate the pursuit of science or engineering as a career goal. Moreover, from their responses on the final course evaluation form and on the separate application form for a summer internship program (completed by fifteen students), it appeared that the students were more focused on technical interests. While we cannot say if there was an earlier unexpressed interest in the topical issues presented, it is clear that these ninth (and some tenth) grade students were sufficiently sophisticated to decide that genetic engineering of seaweeds was exciting and that investigating the use of biopolymers in concrete was not exciting—or the reverse. Moreover, some students expressed an interest in having demonstrations and experiments with animals and in further pursuing research on the topics we had discussed. (Note: Other than showing an animal to the high school students, demonstrating experiments by using live animals is illegal in Massachusetts.)

At the conclusion of our second quarter pilot program we devoted the last session to a buffet, followed by the awarding of certificates. (An award was made to students who missed three or fewer sessions.) Two faculty members who had graduated from this school spoke briefly, as did the dean of the college of engineering. The students seemed to be pleased both with the special awards session and with the opportunity to complete a course evaluation form. In general, throughout the pilot project we treated the students as adults and found that they acted like adults.

FUTURE PLANS

Our future plans call for bringing together high school science teachers and university professors to plan the introduction of applications of modern biotechnology into high school science courses. In our

first summer session, we anticipate that high school science teachers will wish to learn more about modern biotechnology, and especially its social applications. Thus, a series of informal lectures and hands-on participative demonstrations will be given by professors who are well-established in selected areas of modern biotechnology. Further, since the professors will need to gain an understanding of what high school science teachers believe is appropriate for presentation to high school students, the high school teachers will present informal seminars dealing with their experiences in introducing the newer aspects of science and technology into their courses.

Looking ahead, we also plan to initiate some of the key recommendations from this summer study program into a pilot program to be initiated during the following academic year. This pilot program will involve the introduction of key recommendations from the summer study sessions into the high school classrooms and laboratories. We also anticipate that the professors will give demonstrations and will involve students in "show-and-tell" type experimental themes coupled with measurement orientations (*i.e.*, we wish to integrate quantitation into all demonstrations). Further, the pilot program will include regularly scheduled monthly meetings with the professors and the high school teachers in order to assess progress and to discuss problems. □

REVIEW: Hazardous Waste

Continued from page 147

teaching and research, consulting, and governmental experience to supplement his BS, MS, and PhD in chemical engineering, and his MBA. Thus, he has real design and management experience in waste treatment technologies and has taught the material in the classroom to engineering students. Moreover, he has organized countless professional meetings dealing with the HWM area for AIChE.

The text covers the entire field in 450 pages. It begins with the basic definition of hazardous waste in general terms and provides an historical background for the field, both in the United States and Europe. The latter is an important perspective because European concerns predate ours in many respects. Several important case studies are provided to place the field in its political context and to provide introductory technical insight. Next, the process of risk assessment is introduced with case studies. Then the author provides two chapters which discuss the driving force behind the HWM area: federal legislation.

The background begins with the Rivers and Harbors Act of 1899 and includes explanatory pages on the Atomic Energy Act, the National Environmental Policy Act, the Occupational Safety and Health Act, the Air Quality and Water Quality Acts, the Solid Waste Disposal and Resource Recovery Acts, the Toxic Substances Control Act (TSCA), the Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response, Compensation, and Liabilities Act (CERCLA), and the Superfund Amendments and Reauthorization Act (SARA) among others. The final chapter of the introductory portion of the book provides a detailed technical and legal definition of hazardous waste.

The author then shifts to the technical side of the field. First, he focuses on waste minimization, which is perhaps the most important future concern in HWM. This chapter treats the managerial portion of waste minimization, including policy, benefits, priorities, and tracking and auditing systems. This chapter does not treat the engineering design aspects of waste minimization, the heart of which is chemical engineering, because the pedagogical aspects of this discipline have not yet been developed and are rightfully the subject of another book. Next, Wentz covers chemical, physical, biological, and thermal treatment of hazardous waste in two excellent chapters which incorporate both descriptive material and fundamental design equations. Consistent with earlier portions of the text, these chapters provide a legal standard context and case studies.

In logical order, Wentz turns to the transportation of hazardous waste. Included are federal regulations, DOT and EPA procedures, definitions of shippers and carriers, and the regulation of each. Record-keeping, reporting, and manifesting are treated with examples and the uniform manifest. State and local regulations, with emphasis on notification, routing, emergency response procedures and equipment, and right-to-know laws, are covered.

Finally, the text treats land disposal, groundwater contamination, injection well disposal, process siting and site remediation. Again, the author has achieved comprehensive coverage of hydrology, groundwater chemistry, contamination, design of monitoring wells, regulations, siting, and classification of wells, with design equations and case studies. The Superfund law, the Hazard Ranking System (HRS), and National Priority List (NPL), together with containment and treatment technologies and vitally impor-

tant financial strategies, play a role in the final chapter.

Wentz has packed the text with important information needed by the practitioner, and he definitely achieves his stated goal in the preface "to integrate a broad field into a single book that deals with all phases of this important subject." He provides appendices of listed wastes and a surprising depth of coverage despite the comprehensive nature of this teaching text. The problems at the end of each chapter could be more extensive, but are certainly at the right level for the senior undergraduate or beginning graduate student for whom the text is intended. A solutions manual is available.

This subject has and will continue to move quickly, so much of the illustrative data in the early chapters is already dated, but the need for this book should warrant frequent updates. It is clearly a survey text, so that one should not expect in-depth coverage of every topic; we continue to need other texts, but Wentz has given us a start.

At Wayne state University, we offer several dozen hazardous waste management courses as part of our regular chemical and civil engineering degree programs, but chemical engineering also administers a Graduate Certificate Program [4] and a full MS in Hazardous Waste Management [5,6]. Most schools offering an extensive HWM program have a survey course as the entry point [3]. For our introductory course, we have adopted Wentz's Hazardous Waste Management as the required text, but cannot cover the text in a two-credit semester offering. One of the highest compliments that I can pay to the text is that our civil engineering faculty also use it for their landfill course, which is well beyond the scope of our introductory course.

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STOCHASTIC MODELING OF CHEMICAL PROCESS SYSTEMS

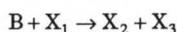
Part 3: Application

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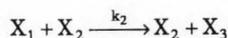
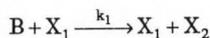
IN THIS FINAL part of our three-part series on stochastic modeling of chemical process systems, the master equation derived in Part II is employed to model a chemically-reacting system. The purpose is two-fold: the first is to demonstrate the application of the master equation, and the second is to show that fluctuations will be negligible in a reacting system where the number of discrete entities (molecules) is large. Nevertheless, this is not always the case for a system with a relatively small population, *e.g.*, a bubbling fluidized-bed combustor for large coal particles. Such a system also is not uncommon at the outset and conclusion of any process; these periods are the most critical from the standpoint of operation, monitoring, and control.

EXAMPLE CALCULATION WITH THE MASTER EQUATION

For the reaction



its elementary steps can be expressed as



We shall assume that these reactions take place in a well-mixed vessel of volume Ω under isothermal conditions. The proper modeling of concentration fluctuations in the system requires knowledge of the elementary (molecular) reaction mechanism. However, this information is not known in many industrially relevant reactions; thus, phenomenological kinetic models are employed [1]. Such phenomenological models, however, are not sufficient to determine the exact nature of the inter-

nal fluctuations.

We shall also assume that the feed stream to the reactor contains only component X_1 and that the system has a mean residence time of τ_s . Of the three components involved in the reaction steps, X_1 and X_2 will be variable, while B is assumed to be held at a constant concentration. Finally, for deriving a stochastic model, it will be assumed that each molecule behaves independently and thus will react with a probability derivable from the rate equations of chemical kinetics [2].

Rate of Transition Functions

If we define N_1 and N_2 as the numbers of molecules of component X_1 and X_2 , respectively, in the reaction volume, the following rates of transition, $W_t(n_1, n_2; \xi_1, \xi_2)$, can be derived [2,3]:

$$W_t(n_1, n_2; 1, 0) = \frac{\Omega C_f N_A}{\tau_s} \quad (1)$$

$$W_t(n_1, n_2; -1, 0) = \frac{n_1}{\tau_s} + \frac{k'_2}{\Omega} n_1 n_2 \quad (2)$$

$$W_t(n_1, n_2; 0, -1) = \frac{n_2}{\tau_s} \quad (3)$$

$$W_t(n_1, n_2; 0, 1) = B k_1 n_1 \quad (4)$$

The first of these is due to the entrance of molecules of X_1 into the reactor; hence, $\Omega C_f N_A / \tau_s$ is the number of molecules of X_1 entering the reactor per unit time. The second expression, Eq. (2), is due to molecules of X_1 leaving the reactor and to the second chemical reaction. The third, Eq. (3), corresponds to molecules of X_2 leaving the reactor. Finally, the fourth expression corresponds to the first chemical reaction. Note that the k'_2 is the second-order rate constant in terms of molecules instead of moles with units of time (volume · molecules). The rate constant in terms of moles, k_2 , can be obtained by multiplication of k'_2 by the Avogadro number, N_A .

Jump Moments

With the aid of Eqs. (9) and (11) in Part II, the jump moments follow directly from Eqs. (1) through (4). These are

$$A_1 = \frac{\Omega C_f N_A}{\tau_s} - \frac{n_1}{\tau_s} - \frac{k_2'}{\Omega} n_1 n_2 \quad (5)$$

$$A_2 = -\frac{n_2}{\tau_s} + B k_1 n_1 \quad (6)$$

$$B_{1,1} = \frac{\Omega C_f N_A}{\tau_s} + \frac{n_1}{\tau_s} + \frac{k_2'}{\Omega} n_1 n_2 \quad (7)$$

$$B_{1,2} = B_{2,1} = 0 \quad (8)$$

$$B_{2,2} = \frac{n_2}{\tau_s} + B k_1 n_1 \quad (9)$$

The application of Eqs. (10) and (12) from Part II followed by Eqs. (14) and (15) from Part II leads to the coefficient matrices of the linearized Fokker-Planck equation governing the fluctuations, *i.e.*,

$$\tilde{A} = [\tilde{A}_{i,j}] = \begin{bmatrix} -\frac{1}{\tau_s} - k_2' \phi_2 & -k_2 \phi_1 \\ B k_1 & -\frac{1}{\tau_s} \end{bmatrix} \quad (10)$$

$$\tilde{B} = [\tilde{B}_{i,j}] = \begin{bmatrix} \frac{C_f N_A}{\tau_s} + \frac{\phi_1}{\tau_s} + k_2 \phi_1 \phi_2 & 0 \\ 0 & \frac{\phi_2}{\tau_s} + B k_1 d_1 \end{bmatrix} \quad (11)$$

Average Value Equations

The zero-order terms in Eqs. (5) and (6) lead to the following expressions for the average numbers of molecules of the two components:

$$\frac{d}{dt} \langle N_1 \rangle = \frac{\Omega C_f N_A}{\tau_s} - \frac{\langle N_1 \rangle}{\tau_s} - \frac{k_2'}{\Omega} \langle N_1 \rangle \langle N_2 \rangle \quad (12)$$

$$\frac{d}{dt} \langle N_2 \rangle = -\frac{\langle N_2 \rangle}{\tau_s} + B k_1 \langle N_1 \rangle \quad (13)$$

Dividing both sides of these expressions by ΩN_A results in the familiar rate equations for reactions in a well-mixed reactor in terms of molar concentrations

$$\frac{dC_1}{dt} = \frac{1}{\tau_s} (C_f - C_1) - k_2 C_1 C_2 \quad (14)$$

$$\frac{dC_2}{dt} = -\frac{1}{\tau_s} C_2 + B k_1 C_1 \quad (15)$$

Covariances

In addition to the expressions for the average concentrations, the stochastic model also yields expressions

... the master equation ... is employed to model a chemically-reacting system. The purpose is two-fold: ... to demonstrate the application of the master equation, and ... to show that fluctuations will be negligible in a reacting system where the number of discrete entities (molecules) is large.

for the concentration fluctuations. The coefficient matrices, Eqs. (10) and (11), are employed in conjunction with Eq. (23) in Part II for this purpose.

When we divide both sides of the resultant expressions by N_A^2 , we obtain the following expressions in terms of molar concentrations:

$$\begin{aligned} \frac{d}{dt} \text{Var}[C_1] &= -2 \left(k_2 C_2 + \frac{1}{\tau_s} \right) \text{Var}[C_1] \\ &\quad - 2 k_2 C_1 \text{Cov}[C_1, C_2] + \frac{1}{\Omega N_A} \left(\frac{C_f}{\tau_s} + \frac{C_1}{\tau_s} + k_2 C_1 C_2 \right) \end{aligned} \quad (16)$$

$$\begin{aligned} \frac{d}{dt} \text{Cov}[C_1, C_2] &= - \left(\frac{2}{\tau_s} + k_2 C_2 \right) \text{Cov}[C_1, C_2] \\ &\quad - k_2 C_1 \text{Var}[C_2] + B k_1 \text{Var}[C_1] \end{aligned} \quad (17)$$

$$\frac{d}{dt} \text{Var}[C_2] = 2 B k_1 \text{Cov}[C_1, C_2] - \frac{2}{\tau_s} \text{Var}[C_2] + \frac{1}{\Omega N_A} \left(\frac{C_2}{\tau_s} + B k_1 C_1 \right) \quad (18)$$

This set of coupled differential equations can be solved for the covariance and variances of the fluctuations. For our purposes, it suffices to note that the resultant expressions will be proportional to $(\Omega N_A)^{-1}$. Since $N_A \approx 10^{24}$, we can safely conclude that unless Ω is very small ($\approx 10^{-24}$), the concentration fluctuations will have a standard deviation in the order of 10^{-12} mol/volume. Such fluctuations, being imperceptible to most, if not all, instruments commonly employed in practice, must be considered negligible.

Correlation Functions

According to Eq. (25) in Part II, the expressions for the auto- and cross-correlation functions are, respectively

$$\frac{d}{d\tau} K_{i,1}(\tau) = - \left(k_2 C_2 + \frac{1}{\tau_s} \right) K_{i,1}(\tau) - k_2 C_1 K_{i,2}(\tau), \quad i=1,2 \quad (19)$$

$$\frac{d}{d\tau} K_{i,2}(\tau) = B k_1 K_{i,1}(\tau) - \frac{1}{\tau_s} K_{i,2}(\tau), \quad i=1,2 \quad (20)$$

The initial conditions for these equations are the steady-state covariances. Since these are proportional

to $(\Omega N_A)^{-1}$, so will be the correlation functions. The real parts of the eigenvalues for the system of equations, Eqs. (19) and (20), are negative and, most important, functions of the macroscopic rate constants. If the fluctuations were measurable, it would be possible to calculate the rate constants from *steady-state* experiments. However, this is precluded in the chemically-reacting system under consideration because of the immeasurability of fluctuations due solely to the stochastic combination of individual molecules.

CONCLUDING REMARKS

We have seen that for a Markovian system, where the rates of transition can be formulated, the master equation can be solved approximately for the means and correlation functions of the random variables of interest. Thus it is possible to study the effects of stochastic kinetics on the evolution of discrete populations and on the behavior of the system. This is impossible to accomplish by the conventional deterministic approach that leads to equations only for the means.

The master equation with the attendant System Size Expansion offers advantages over other stochastic formulations. For example, we have seen that the well-known problem of coupling arises between moments of differing orders for a nonlinear system. In most formulations this problem is circumvented by assuming independence among random variables or by resorting to an *ad hoc* procedure. The System Size Expansion follows a more rational pathway. Its power series expansion retains a linear coupling between the means and fluctuating components of the random variables—a coupling ignored or distorted when an *ad hoc* approach is used. In a system where the System Size Expansion is not applicable, the majority of the *ad hoc* procedures are also invalid, and the system is best handled by a simulation procedure, *e.g.*, the Monte-Carlo method.

The magnitude of internally-generated fluctuations has been found to decrease as the number of independent entities increases. This, in turn, has led us to conclude that internal fluctuations due to molecular interactions in a chemically-reacting system are negligible. Nevertheless, it does not imply that the fluctuations in a molecular system will be negligible in general. Indeed, all systems are molecular, but fluctuations are often present. Therefore, the key to modeling fluctuations is the proper identification of their sources.

It is worth noting briefly that the auto- and cross-correlation functions have characteristic time constants which are functions of the macroscopic rate constants.

This observation should be of interest to the experimentalist wishing to determine the constants since the correlation functions are measured for systems operating at steady-state. It is known in physics as the fluctuation-dissipation theorem and is used in measuring various quantities, including diffusion coefficients.

In this series of articles we have concentrated on the stochastic modeling of internal fluctuations in systems amenable to a description involving a stochastic population balance. Another important area of stochastic modeling involving external fluctuations, *i.e.*, fluctuations generated by the environment of the system, is best described by stochastic differential equations that have not been discussed here. The reader will find details on the formulation and solution of model equations for external noise systems in the monographs by van Kampen [2], Gardiner [4], and Horsthemke and Lefever [5]. The last gives an excellent introductory treatment of the effects of multiplicative (noise terms appearing in the governing equations multiplied by the dependent variables) and additive noise in single variable systems. It is shown that additive noise does not change the steady-state solution diagram in single variable systems (all stable and unstable solutions exist at the same parameter values), whereas multiplicative noise can lead to an even richer steady-state solution diagram. New solution branches are generated as the noise intensity increases. Such behavior is known as a “noise induced transition” to emphasize its dependency on the presence of external multiplicative noise.

As remarked at the outset of this series, systems with stochastic components are prevalent in chemical engineering. Currently, several excellent treatises on stochastic modeling stressing physical and chemical systems are available [2,4,5]. These sources are highly recommended to those wishing to expand their knowledge of the subject. In addition, we feel that it is necessary to obtain at least a rudimentary understanding of probability theory, random variables, and stochastic processes as presented in classical treatises such as Feller [6], Karlin and Taylor [7], or, for the more mathematically inclined, Gihman and Skorohod [8]. The reader interested in stochastic differential equations will find an understandable but rigorous presentation in the monograph by Arnold [9]. The introduction of stochastic modeling concepts into basic chemical engineering education is an important step in furthering the ability of chemical engineers to understand the complex systems they frequently encounter. The wide availability of readable, well-written material on stochastic modeling in the modern literature offers an excellent opportunity for chemical engineers to incorporate new methods and fresh

ideas into the modeling of chemical process systems.

ACKNOWLEDGEMENTS

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NOTATION

A_i	first jump moment
$\tilde{A}_{i,j}$	coefficient in expansion of \tilde{A}_i
B	concentration of component B
$B_{i,j}$	second jump moment
$\tilde{B}_{i,j}$	$B_{i,j} / \Omega$
$\text{Cov}[C_i, C_j]$	$\langle C_i C_j \rangle - \langle C_i \rangle \langle C_j \rangle$, covariance of C_i and C_j
C_f	feed concentration of component X_1
C_1	concentration of component X_1
C_2	concentration of component X_2
k_1, k_2	reaction rate constants
k_2'	reaction rate constant in units of molecules
$K_{i,j}(t)$	correlation matrix defined for C_i and C_j as $\langle C_i(0)C_j(\tau) \rangle - \langle C_i(0) \rangle \langle C_j(\tau) \rangle$
N_A	Avogadro number
N_j	number of molecules of component j
$\langle N_j \rangle$	expected value of random variable N_j
$W_t(\{n\}_0, \{n\}_1)$	rate of transition from state $\{n\}_0$ to state $\{n\}_1$

Greek Letters

ξ_i	magnitude of change in random variable N_i
τ_s	mean residence time
ϕ_i	deterministic variable corresponding to macroscopic behavior of N_i
Ω	system volume

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REVIEW: Polymer Chemistry

Continued from page 153.

really descriptive since the authors seek to treat an extremely large fraction of *polymer science* rather than focussing on the narrower topic of *polymer chemistry*. It would be difficult to have included significant computational problems in the present text because the treatment is highly qualitative. Perhaps because of my chemical engineering bias, some actual examples worked out in detail would have been attractive. For example, condensation and free radical polymerization systems are important enough to merit such treatment even in an overview book such as this.

The references given at the end of the chapters are good, and, in fact, are some of the classics in the various areas. Most of the references are rather old, with only a sprinkling of new sources. While this is not a particular problem for an introductory text, it certainly does not reflect the current literature in a way needed for an introductory graduate (or even a more advanced undergraduate) course.

While the light, easily-read approach is ideal for many of the topics discussed in such an introductory text, some topics might have benefitted from a detailed treatment in order to give the student more than a broad-brush appreciation of their importance to the modern polymer field. It is likely that many instructors would feel the need to supplement the material in the areas of 1) polymer physical properties and their relationship to structure, 2) thermal methods of analysis (DSC, TGA, etc.), and 3) reaction kinetics for condensation and free radical systems. Alternatively, of course, one could direct the student to the original references given at the end of the chapters to obtain sufficient detail to have a true appreciation for these principles. If there is any topic which comes close to being missed, it is the important area of polymer-solvent and polymer-polymer thermodynamics. Although the topic of solubility of polymers in solvents is mentioned, the treatment and importance of solution thermodynamics is given practically no coverage.

The authors indicate that the book could be covered in a normal semester or in two quarter periods, and this seems reasonable. Even with supplemental information and exercises given in the areas noted above, the easily-read style and frequent use of drawings make the material easy to read and to understand. Even if some of the more technological topics covered in the last 40% of the book are not discussed in class, they make useful reading for a student seeking an overview of the field. □

PLASMID INSTABILITY IN BATCH CULTURES OF RECOMBINANT BACTERIA

A Laboratory Experiment

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OVER THE LAST FOUR YEARS, we have offered a hands-on laboratory course in biotechnology [1] which accompanies a lecture course on "Recent Advances in Biotechnology" for chemical engineering seniors and entering graduate students. Of the seven experiments normally conducted in this course, an experiment on plasmid instability in recombinant cultures pertains most directly to the modern biochemical engineering principles and the recent advances in biotechnology discussed in the lecture course. Further, the experiment is the most recently developed and will probably be more difficult to reproduce in other chemical engineering laboratories. It is our objective here to discuss the important theoretical and practical aspects in more detail so that this novel experiment may be more easily duplicated in other undergraduate laboratory courses.

Recombinant bacterial cultures are inherently unstable. Bacterial cells which harbor recombinant plasmids are commonly at a disadvantage when competing with plasmid-free cells for essential nutrients. Since the synthesis of a recombinant product depends entirely on the stable maintenance of the plasmid-bearing strain, a great body of research has dealt with the mechanisms of plasmid instability. Many methods are being pursued to genetically eliminate plasmid instability [2]. One technique, completely successful at the laboratory level and employed in this experiment, is to use selective media with an antibiotic resistance marker on the plasmid vector. Two dominating factors have been most often linked to the observed culture instabilities: plasmid segregation and a "growth-rate

differential" between plasmid-bearing and plasmid-free cells. Plasmid segregation is a result of uneven plasmid partitioning from the mother to daughter cells upon cell division and therefore generates plasmid-free from plasmid-bearing cells. The growth rate differential is due to the redirection of cellular catabolic and anabolic activity in the recombinant cells while they synthesize the desired product. Consequently, plasmid-bearing cells do not have full use of their own resources and grow more slowly than those which are plasmid-free. The plasmid-free cells born by plasmid segregation are thus able to rapidly overtake the overall population.

This laboratory experiment is intended to familiarize the student with microbiological techniques as well as the analysis of exponential growth in bioreactors. Further, students are introduced to the experimental and theoretical characterization of instabilities observed with recombinant bacteria as



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The laboratory is designed so that the students are exposed to problem solving methods both as individuals and as participants of a group. The handout . . . is not a "cookbook" step-by-step account of the lab procedure—such labs often lack meaningful educational value because they preclude active student participation. Instead, the instructor should create an environment containing appropriate tools without dictating the precise methods.

noted above. The laboratory is designed so that the students are exposed to problem solving methods both as individuals and as participants in a group. The student lab handout (available from the authors) is not a "cookbook" step-by-step account of the lab procedure—such labs often lack meaningful educational value because they preclude *active* student participation. Instead, the instructor should create an environment containing the appropriate tools without dictating the precise methods.

The pre-lab discussion emphasizes the theoretical background and analysis in addition to the laboratory techniques. Demonstrations for sterile serial dilutions, plating, and optical density measurements are given. Typically, the laboratory is divided into groups of three or four students, while the written reports are prepared on an individual basis. In this way, group efforts are emphasized but each student is ultimately responsible for his/her own work.

EXPERIMENT

Background

The pioneering theoretical work was a simple model which could be employed to predict the population dynamics of a mixed-population batch culture during exponential growth [3]. This work is summarized below. The growth of the plasmid-bearing, P, and plasmid-free, N, subpopulations can be described

$$\frac{dP}{dt} = (1-p)\mu^+ P \quad (1)$$

$$\frac{dN}{dt} = p\mu^+ P + \mu^- N \quad (2)$$

where t is time (hr), p is the segregation coefficient (dimensionless), μ is specific growth rate (hr^{-1}), and superscripts $+$ and $-$ are cells with and without plasmid, respectively. By setting

$$P = P_0, \quad N = N_0 \quad \text{at} \quad t = 0 \quad (3)$$

from Eq. (1) and (3), we obtain

$$P = P_0 e^{(1-p)\mu^+ t} \quad (4)$$

and from Eq. (2), (3) and (4), we obtain

$$N = N_0 e^{\mu^- t} + \frac{p\mu^+ P_0}{(1-p)\mu^+ - \mu^-} \left[e^{(1-p)\mu^+ t} - e^{\mu^- t} \right] \quad (5)$$

TABLE 1

Limiting Cases for Graphical Analysis of Eq. 7

Case	Dominant Factor	Initial Condition
I	growth rate differential	$N_0 > 0$
II	growth rate differential	$N_0 = 0$
III	plasmid segregation	$N_0 > 0$
IV	plasmid segregation	$N_0 = 0$

The fraction of plasmid-bearing cells can then be written as

$$F \equiv \frac{P}{P+N} = \frac{P_0 e^{(1-p)\mu^+ t}}{P_0 e^{(1-p)\mu^+ t} + N_0 e^{\mu^- t} + \frac{p\mu^+ P_0}{(1-p)\mu^+ - \mu^-} \left[e^{(1-p)\mu^+ t} - e^{\mu^- t} \right]} \quad (6)$$

We have linearized this expression for easier graphical analysis of laboratory data

$$\ln \left(\frac{1}{F} + A - 1 \right) = \ln \left(A + \frac{N_0}{P_0} \right) + [\mu^- - (1-p)\mu^+] t \quad (7)$$

where

$$A \equiv \frac{\mu^+ p}{\mu^- - \mu^+ + \mu^+ p}$$

Eq. (7) can be applied to four separate cases so that a slope and intercept can be obtained from the data yielding an important experimental parameter which characterizes the culture dynamics of any experimental plasmid/host system (see Table 1).

The culture instability for our experimental system is dominated by the growth rate differential since the plasmid exists at a high copy number (low segregation probability). Therefore, we simplify Eq. (7) for our experiment (Case I). If $\mu^+ p \ll \mu^- - \mu^+$, then

$$A \equiv \frac{\mu^+ p}{\mu^- - \mu^+} \ll 1$$

and

$$\ln \left(\frac{1}{F} - 1 \right) = \ln \left(\frac{N_0}{P_0} \right) + (\mu^- - \mu^+) t \quad (8)$$

so that the difference in growth rate between the plasmid-bearing and plasmid-free cells is the slope of this linear relationship.

Materials and Methods

A. Culture Conditions

E. coli RR1, obtained from Bethesda Research Laboratories (BRL), was transformed with the plasmid pBR329 (which confers resistance to tetracycline, ampicillin, and chloramphenicol) also from BRL (according to Maniatis, *et al.* [4]). *E. coli* RR1 is used as the host bacterium because of its high transformation efficiency. pBR329 is a model plasmid which exists at high copy numbers, but could easily be replaced by any ColE1-type plasmid. Experiments were performed in shake flasks controlled at 37°C in a water bath shaker (New Brunswick Scientific Model RW-650). Media (M9—a minimal media) was prepared according to Maniatis, *et al.* [4]. The host bacterium requires supplemental leucine, proline, and vitamin B1 in defined media. These were added at levels of 41, 164, and 0.166 µg/ml respectively (Fisher Scientific). Bacterial cultures, grown overnight, in the presence of antibiotic (tetracycline, 12 µg/ml), were diluted ($\approx 1/20$ dilution) and grown again for approximately one hour in several flasks containing media identical to that used in the subsequent experiments. In this way, we were assured that each inoculum was in the exponential growth phase at conditions identical to those of the experiments and hence, preculture metabolic variation was eliminated. Each inoculum was approximately 1 ml for every 100 ml of culture media.

B. Growth Rate Measurements

Optical density (absorbance at 600 nm) was measured in the linear range (0.05 to 0.25 OD units) on a Beckman DU-50 Spectrophotometer. More dense samples were diluted with sterile water to obtain OD in the linear range. The OD was corrected for the background absorbances of the differing sterile media.

C. Fraction Plasmid-bearing Cells, F

The fraction of plasmid-bearing cells was determined by replica plating. Samples were diluted in sterile water until 40 µl contained approximately 100 to 300 cells. This quantity was spread on an LB agar plate and incubated overnight. Sterile felt was used to transfer the colonies from the original LB plate to one plate each of LB and LB with tetracycline (12 µg/ml). The number of colonies on the LB_{tet} plate divided by the number on the second LB plate is the fraction recombinant cells. Frequently, replica plating was performed on LB_{amp} plates in addition to LB_{tet} in order to confirm the plasmid structural stability.

Additional Precautions

Extra care must be taken to ensure the quality of data so that statistical analysis can be performed on the results. We conduct the growth experiments in a modified minimal medium (M9, Maniatis, *et al.* [4]) so that the growth-rate curve is linear for at least five hours. Rich media should be avoided since the growth rate continually decreases as some nutrients become depleted. Three flasks are prepared: (1) *E. coli* RR1 (no plasmid), (2) *E. coli* RR1 with pBR329 (100% plasmid-bearing), and (3) a mixed culture of the previous two. A detailed, step-by-step procedure is available from the authors. However, a few more subtle points are

- It is advantageous to start the mixed culture (flask 3) at $F \approx 0.9$ or at $F \approx 0.4$, since the standard deviation in replicate plating is \sqrt{nNP} where n is

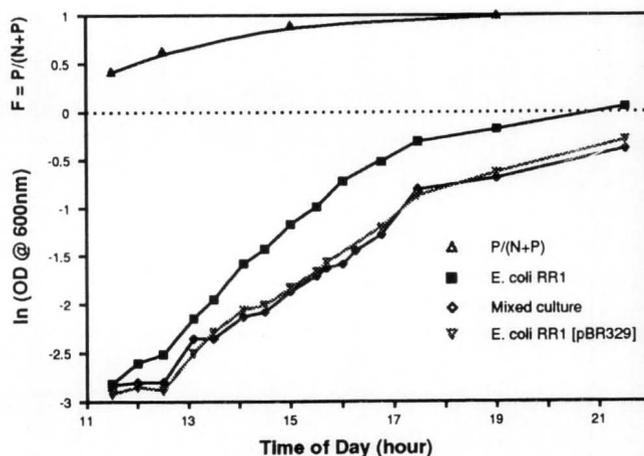


FIGURE 1. Growth in shake flasks (a first attempt).

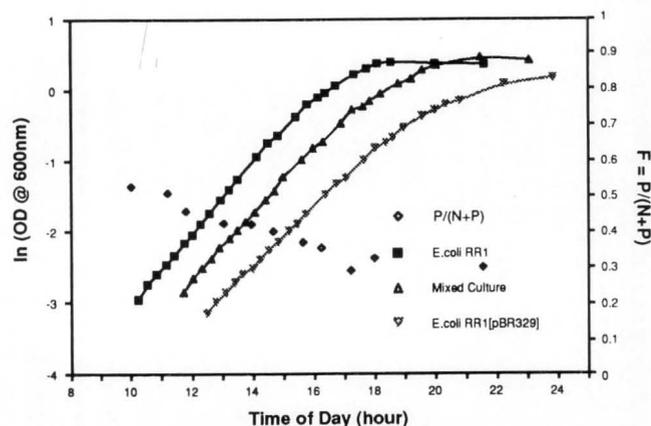


FIGURE 2. Optical density versus time for three cultures: plasmid-free, mixed, and plasmid-bearing. F is also included from the mixed culture.

the number of colonies transferred [5] and is highest around 50% plasmid-bearing.

- The plasmid-bearing cells (grown overnight in media containing antibiotics) must be washed in sterile media containing no antibiotic before inoculating the experiments. This ensures that (1) no antibiotic is transferred to the mixed culture flask which could kill the plasmid-free cells (see Figure 1), and (2) the plasmid-bearing population will be free to segregate so that μ^+ calculated from OD measurements in this flask is accurately ascribed to the plasmid-bearing cells (F should be measured in this flask as well).
- The washed cells should be equilibrated in 1 ml sterile media for one hour at 37°C before inoculating the experiments so that the cells are

exponentially growing upon inoculation in the experiment flasks and smooth data are obtained from the start (see Figure 1 vs. Figure 2).

- Although it may seem cumbersome, take data frequently (approximately every twenty minutes for OD and every forty minutes for F) so that statistical significance can be established.

Results

Figure 1 is an example of a first attempt at this experiment. None of the above mentioned points were performed, and consequently this experiment was of no value. Note that the mixed culture F actually increased with time (the plasmid-free cells were killed by residual antibiotic).

The experiment illustrated in Figure 2 was successful. The growth rates of the cultures are listed in Table 2.

In Figure 3, $\ln(1/F - 1)$ is plotted versus t . The slope, $(\mu^- - \mu^+)$, was 0.114 hr^{-1} and 95% confidence limits were $\pm 0.024 \text{ hr}^{-1}$. The measured difference was 0.094 hr^{-1} (0.511-0.417) which is within the 95% confidence limits of $(\mu^- - \mu^+)$ found from the plot in Figure 3. It is important to note that the value of p is therefore not significantly different than zero. The measured F from the *E. coli* RR1 [pBR329] culture was always unity which also demonstrates that $p \cong 0$. The growth of the mixed culture can be predicted from the growth rates of the other two flasks and the initial OD (P_0 and N_0). The predicted growth of the mixed culture and the actual data are shown in Figure 4. Excellent agreement between the experiment and predictions is obtained during the exponential phase, for which the model equations are appropriate.

A different experimental host/vector system (with low copy number and small growth rate differential, so that $\mu^+ p \gg \mu^- - \mu^+$, Cases III and IV) can lead to an indirect measurement of the plasmid copy number, N_p . The data (F) are plotted using a slightly

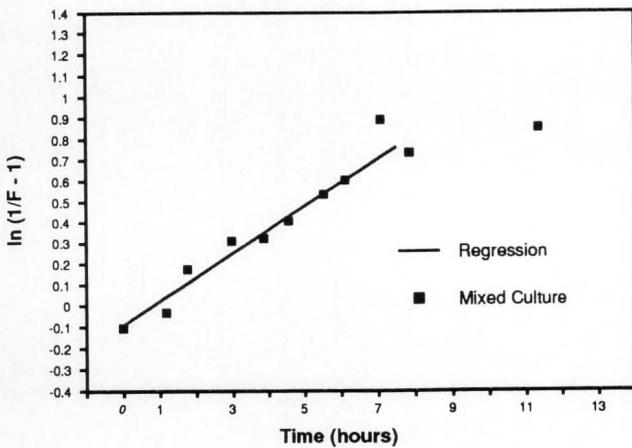


FIGURE 3. $\ln(1/F - 1)$ versus time. This is the reduced form of Eq. (7) for Cases I and II. The slope of this line is $(\mu^- - \mu^+)$.

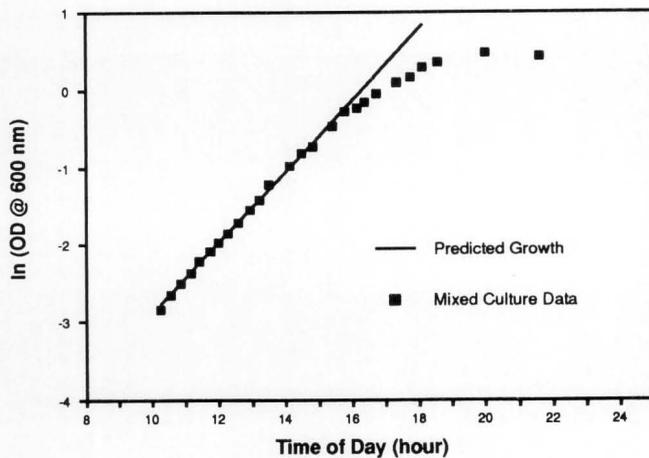


FIGURE 4. Optical density versus time. Predicted values are based on μ^+ (plasmid-bearing culture) and the results from Figure 3.

TABLE 2
Specific Growth Rates and 95% Confidence Limits for the Three Shake Flask Cultures

Culture	μ hr^{-1}	$\pm 95\%$ limits on μ
<i>E. Coli</i> RR1	0.511	0.008
Mixed Culture	0.461	0.010
<i>E. coli</i> RR1 [pBR329]	0.417	0.006

different simplification of Eq. (7):

$$\ln\left(\frac{1}{F}\right) = \ln\left(1 + \frac{N_p}{P_0}\right) + (\mu^+ p)t \quad (9)$$

where the slope yields p . N_p can then be calculated using the following results from Seo and Bailey [6]

$$p = 1 - \frac{\ln(2-\delta)}{\ln(2)} \quad \text{and} \quad \delta = 2^{1-N_p} \quad (10)$$

The experimental measurement for N_p is quite labor intensive.

SUMMARY

This lab can provide an introduction to microbiological techniques, mathematical modeling, and statistical methods while studying a problem of current importance in biotechnology. As previously mentioned, two handouts are available from the authors: one describes the mathematical and experimental procedures in detail, and the other is the pre-lab handout for the students. Over the past three years, this laboratory has evolved into the present form and continues to be enhanced from the student input which is requested in their written reports.

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REVIEW: Physical Polymer Science

Continued from page 135.

American Chemical Society has taken action. The ACS Committee on Professional Training has issued guidelines for "approved degree programs" [*Chem. & Eng. News*, p 49, May 1, 1989]. In addition to a core curriculum of elementary, organic, and physical chemistry, the approved program in chemistry/polymers calls for two semesters of polymer science (physical and organic), laboratory work, and an advanced course.

Sperling has written a textbook which fits the ACS criterion admirably. In general, the topics covered are those suggested for a course in Physical Chemistry of Polymers in a syllabus issued by the Joint Polymer Education Committee of the ACS (*Polymer Education Newsletter*, Spring, 1989). Since

the book presupposes no previous knowledge of polymers beyond the usual undergraduate organic and physical chemistry courses, the first chapter is a brief introduction on polymerization which mainly serves to supply a vocabulary of basic polymer terminology.

In the first third of the book, a chapter on chain structure and configuration includes discussion of some methods of characterization. This is followed by chapters describing concepts of molecular weight as well as solution and phase behavior.

The remainder of the book emphasizes properties of bulk polymers. This includes chapters on crystallinity, classes, and rubber elasticity. Viscoelasticity and mechanical behavior (failure tests) complete the coverage.

The ACS Syllabus for a course in Physical Chemistry of Polymers is rather broad and includes some topics not covered in Sperling's book. Many chemical engineers would probably have been exposed to rheology in other courses so the omission of non-Newtonian flow (at the level of the power-law and the Ellis model, for example) can be overlooked. The ACS syllabus also suggests topics in polymer processing (molding, extrusion, etc.) which are beyond the scope of the present book.

In this day when most polymer books tend to be collections of papers presented at meetings, a textbook with a single author is something of a novelty. The unified viewpoint and consistency of treatment in this book should make it very convenient to use as a text. Each chapter concludes with a "Homework" section containing both numerical and essay-type questions which are useful for self-study or as class assignments. In addition to the many specific references in each chapter, there are suggestions for general reading, most of which are authored (rather than edited) books. The language of the text is quite easily understood and the general organization is neat and consistent.

In addition to the chemistry/polymers topic, approved curricula in specialty areas of chemistry/biochemistry and chemistry/education also have been adopted by ACS. It is noteworthy that in commenting on the usefulness of these new options, M.J. Caserio of the ACS Professional Training Committee is quoted as saying, "...90% of the graduates in chemistry who enter the job market will find themselves working in some area dealing with macromolecules." Those of us who labor in the polymer vineyards of chemical engineering have been saying the same thing about our graduates for many years. This book is a welcome addition to the expository literature for teachers and students in the field of macromolecules. □

ACKNOWLEDGMENT

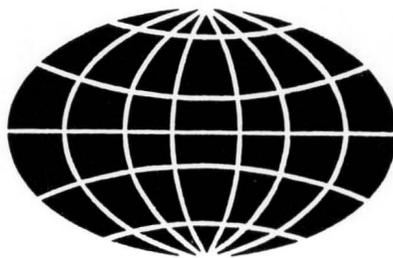
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