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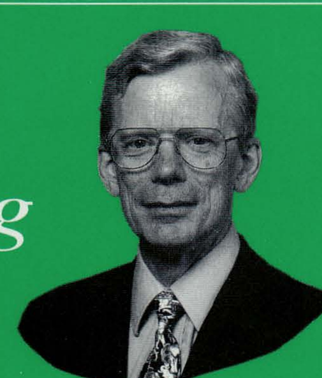
American Institute of Chemical Engineers

Art Westerberg

of Carnegie Mellon University



SPECIAL SECTION - ABET ENGINEERING CRITERIA 2000

Chemical Engineering at . . .

Rose-Hulman
Institute of Technology

EDITORIAL AND BUSINESS ADDRESS:
Chemical Engineering Education
Department of Chemical Engineering
University of Florida • Gainesville, FL 32611
PHONE and FAX: 352-392-0861
e-mail: cee@che.ufl.edu
Web Page: http://www.che.ufl.edu/cee/

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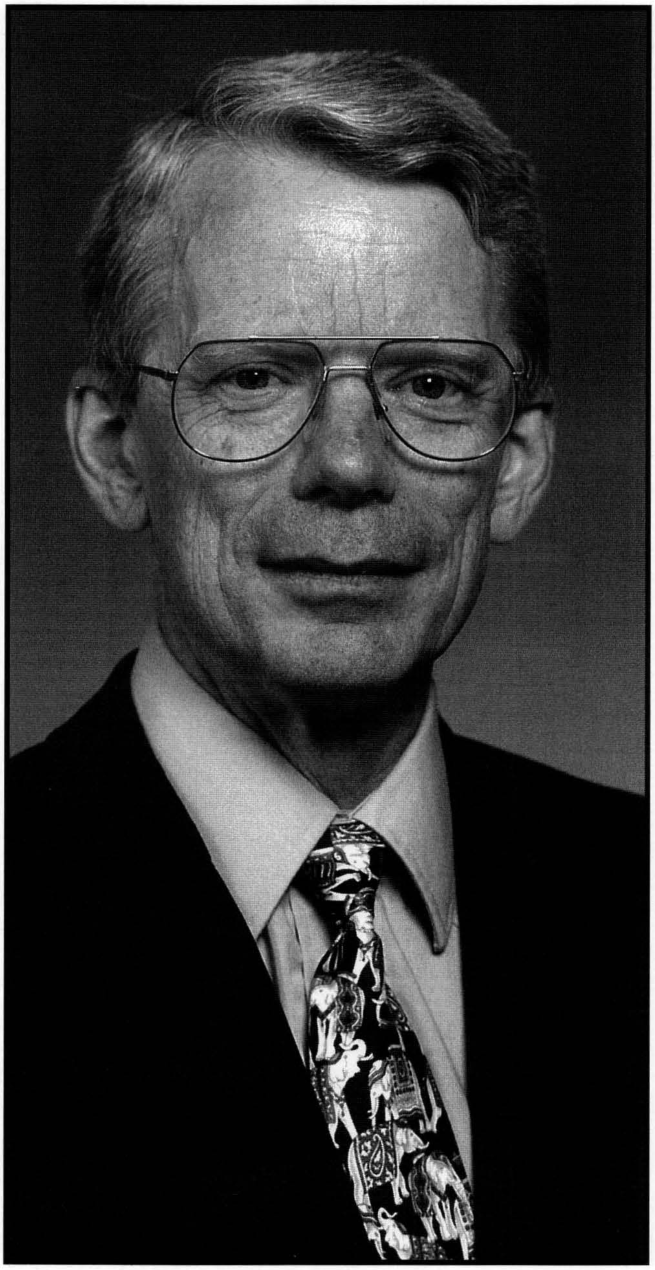
Art Westerberg

... of Carnegie Mellon University



Lorenz Biegler, Ignacio Grossmann,
George Stephanopoulos*
Carnegie Mellon University
Pittsburgh, PA 15213

It is refreshing to find a professor who, having had a profound impact in his field, is also a truly nice, honest individual, well liked and highly respected by all. It is also rare that a single person's career can be used as a measure in describing an entire research area. This is true in Arthur Westerberg's case. He has built a foundation that is used as a roadmap for process systems engineering, a dynamic and highly successful area of chemical engineering. Art approaches both life and research with a great sense of humor and optimism.

BACKGROUND

Arthur W. Westerberg was born in St. Paul, Minnesota, in 1938, and spent his childhood in the farm country of that area. He inherited a practical bent as a problem solver from his father, who provided engineering services for farm equipment and construction. He also inherited a knack for applying general concepts and principles to a variety of different areas, and he later found that those interests were well suited to chemical engineering. He thus found himself in the young and dynamic atmosphere at the University of Minnesota in the late '50s in the company of such trendsetters as Amundson and Aris. After completing his BS degree in

* *Address: Massachusetts Institute of Technology, Cambridge, MA 02139*

[Art] inherited a practical bent as a problem solver from his father . . . .
He also inherited a knack for applying general concepts and principles to a variety of different areas . . .
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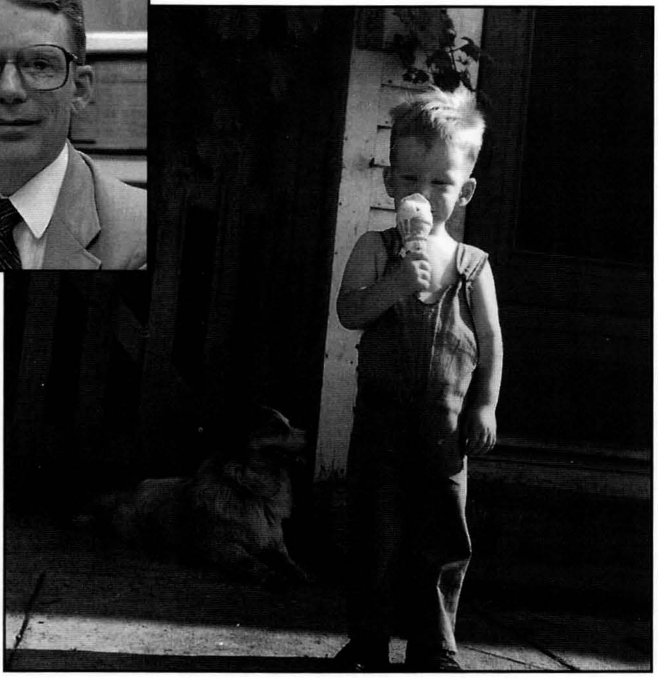


Art Westerberg showed high proficiency in handling cool issues at an early stage.

1960, Art was advised by Amundson to seek out the best graduate education he could find, and his choice was Britain's Imperial College.

American postgraduate students were unusual in Britain in 1960, especially since there were few mechanisms to provide funding for them. Consequently, Art pursued a master's degree at Princeton before accepting the position of Assistant Lecturer at Imperial to study for his PhD. He worked with Professor Roger Sargent, a young faculty member at Imperial who spearheaded the field of process systems engineering (PSE) and who spawned a legacy that includes virtually all PSE researchers. Working together on the development of SPEEDUP (a process simulator widely used today for steady state and dynamic modeling, analysis and optimization), they laid the foundation for computer-aided process analysis. For instance, the Sargent-Westerberg algorithm[1] for partitioning flowsheets and systems of equations is still widely used and quoted in the literature.

After receiving his PhD in 1964, Art joined Control Data Corporation in San Diego as a systems analyst, where he subsequently developed a number of novel codes for numerical analysis. In particular, his work on fast Fourier transforms led to efficient and powerful strategies for resolving chromatographic peaks and spurred the application of this separation technique in analytic chemistry.

The opportunity to teach and do research beckoned, however, and in 1967, Art went to the University of Florida and began his academic career in process systems engineering. PSE was in the embryonic stage in the late 60s, with only a handful of researchers and a host of unsolved and poorly defined problems in process design and analysis. Art's early research pioneered the equation-oriented approach to process flowsheeting. In particular, he focused on systematic methods for developing and solving process simulation problems and extending them so the processes could be optimized as well. In addition, Art, along with other young researchers, banded together to form the CACHE Corporation for education, and he also organized a number of symposia to discuss open research problems and to share experiences. Moreover, this emerging community forged important links to other engineering disciplines where design problems still required definition and solution strategies.

The efforts of the young engineering design community attracted quite a bit of attention in the 70s, especially at (the newly renamed) Carnegie Mellon University (CMU). At CMU, Dean Herbert Toor (with prudent advice from his neighbor, the Nobel laureate Herbert Simon) initiated a Design Research Center in 1975 and strongly influenced the hiring of a number of faculty in the computer-aided design area. They included Gary Powers in chemical engineering, Steven Fenves in civil engineering, and Stephen Director in electrical engineering. It was then only a matter of time before the fertile environment at CMU and Art's own research directions coincided. While Art was on sabbatical with Rudy Motard at the Computer Aided Design Centre in Cambridge, UK, the connection was made, and Art subsequently moved to Pittsburgh and to CMU.

ART'S CONTRIBUTIONS TO PROCESS SYSTEMS ENGINEERING

The following summary does little justice to Art's research contributions. His trailblazing research has strongly influenced the current practice of process simulation, process modeling environments, process optimization strategies, synthesis of chemical processes, and the modeling of engineering activities.

Art's early work on process simulation concentrated on exploiting the structure of process equations. This led to efficient strategies for partitioning equation sets into subsets, tearing strategies for process equations and streams to ensure faster convergence, and selection of decision variables to avoid structural singularities. This work led to the evolution of equation-based strategies for process simulation that employ rapidly converging techniques for simultaneous convergence, which was also enhanced by Art and his colleagues. Developed in the early- to mid-70s, these tools were almost two decades ahead of their time and are now regarded as the basic elements for large-scale modeling and optimization of chemical processes.

With this background, Art's work evolved to handle larger-scale problems and to consider dynamic simulation. Coupled with this task is the importance of handling differential-algebraic equations (and the treatment of high-index systems, where simulations are doomed to failure in a novice's hands) and the extension to structuring calculations for partial differential equations. The thread running through all of these novel contributions was that the simultaneous equation-based paradigm allowed tremendous generality in dealing with a large set of simulation problems in process engineering. This principle was especially powerful when extended to the optimization of these systems. As a result of the simultaneous approach, optimization tasks were raised from a set of tedious case studies to an efficiently integrated part of the simulation platform. The approaches developed by Art and his coworkers paved the way for modern real-time optimization of petrochemical plants and refineries, which has now become the industrial standard.

TABLE 1

Art Westerberg's PhD Students

F.C. Edie
J.A. de Souza Neto
R.L. McGalliard
C.J. De Brosse
J. R. Cunningham
S. Nayak
G. Stephanopoulos
G.L. Allen
J.V. Shah
T.J. Berna
S. Kuru
J. Cerda
M.H. Locke
M.H. Chao
P.A. Clark
M.J. Andercovich
J.B. Hillerbrand, Jr.
S.S. Kim
A.N. Hrymak
J. Vaselenak
R. Banares-Alcantara
N.A. Carlberg
F.D. Carvallo
P.C. Piela
A.K. Modi
O.J. Smith, IV
Y. Chung
R.S. Huss
O.M. Wahnschafft
M.E. Thomas
K.A. Abbott
B. Safrit
Joseph J. Zaher
D. Cunningham
B.A. Allan
V. Rico-Raminez

Coupled with his advances in simulation, Art recognized the importance of developing modeling systems that capture the physical phenomena and topology of processing systems. Here, the challenge is also to embed within modeling systems efficient simulation tools that are easy to use, helpful with diagnostics, and extendable to building very large-scale models. The vehicle for these ideas is the environment that evolved into ASCEND (Advanced System for Computation in Engineering Design). Moreover, development of ASCEND spawned a complementary research effort into the creation of modeling strategies and languages that, like the simulation tools, were concise and efficient and would support the construction of extremely large models. ASCEND has evolved over four generations and continues to be used by a variety of researchers for modeling, simulation, and optimization of steady state and dynamic processes.

Art did not stop with the modeling of processing systems, however. With the use of ASCEND and other design tools in engineering project teams, Art recognized the importance of managing project information among design teams and in developing platforms that support the entire design process. Heading a diverse team of researchers (engineers, computer scientists, and even artists), Art has spent the last decade molding these ideas into the n-dim system in order to support the 'design' of the design process for a project team. Offshoots of this project include products like the LIving REpository (LIRE') that supports a life cycle of information (authoring, searching, editing, publishing, etc.) for a design team.

In tandem with modeling, simulation, and optimization lie Art's contributions to the design of processing systems and the synthesis of chemical processes. Adopting a systems approach to discover and apply underlying concepts for putting processes together, Art attacked a wide variety of problems in process synthesis from a wide variety of approaches. His perspective and grasp of the synthesis problem were envisioned in 1980 in a beautifully written review paper.[2]

Art's contributions in process synthesis can be organized in threads along process lines, starting with the design of heat-recovery networks and evolving to a broad set of separa-

The Westerbergs: Art, Barbara, Ken, and Karl.

tion systems that include distillation, heat-integrated column systems, multi-effect evaporation, and most recently, synthesis of nonideal, azeotropic distillation. In all of these areas, Art and his coworkers sought underlying guiding principles that exploit the nature of the problem and provide an understanding of 'why' the best design had its essential characteristics. Art's approaches to synthesis have been novel and diverse; they include strategies at the cutting edge of development, evolutionary and heuristic strategies, optimization, and the use of artificial intelligence and expert systems. In all of these cases, Art was careful to choose the 'right tool' for the right problem and to develop a synergy between both, in order to develop a deep understanding of the designed system.

It goes without saying that Art's efforts have been recognized by the chemical engineering community through numerous honors and awards. They include membership in the National Academy of Engineering, early recognition in the CAST Computing Award, the AIChE Walker and Founder's Awards, and the E. V. Murphree Award from ACS. At Carnegie Mellon, he received the Swearingen Chair in 1982 and was named University Professor in 1992.

ART'S INFLUENCE ON THE DEPARTMENT

The list of Art's many research contributions does not begin to present a complete picture of his contributions to the Chemical Engineering Department at CMU. Shortly after arriving, Art assumed the position of Director of the Design Research Center (DRC) and proceeded to build up interaction among departments across the campus. Under his leadership, the DRC provided a forum for like-minded faculty to collaborate and learn about design problems and solution strategies in other fields. Tangible results were the creation of a seminar series as well as a widely distributed technical-report series. Art's influence also led to the hiring of several design faculty on campus, including Ignacio Grossmann in Chemical Engineering.

As department head, from 1980-83, Art faced some turbulent times due to transitions in research funding and the departure of several CMU faculty. During his term, Art spearheaded rebuilding the department by hiring almost half of its faculty, including Myung Jhon, Larry Biegler, Mike Domach, Gary Blau (now at Purdue), and Greg McRae (now at MIT). Art enjoyed a brief sabbatical rest in 1983-4 as the Hougen Visiting Professor at the University of Wisconsin. His return to CMU led to a number of important achievements.

From 1985 to 1986, Art led the competition for a new NSF Engineering Research Center in the area of interdisciplinary engineering design. The resulting Engineering Design Research Center (EDRC) was founded on the concept that basic principles and tools for the design process could be generalized across all engineering disciplines, which in turn would lead to a more fundamental understanding of how to improve the cost, quality, and time for developing designs.

Art served as the first EDRC director from 1986-1989, and his leadership fostered a culture of interdisciplinary research and showed how design research cuts across domains.

Art's presence in the EDRC (and its successor, the Institute for Complex Engineered Systems (ICES)) remains strong through his guidance of the n-dim group and his advice and service on the ICES board. Within the chemical engineering department, many of us look to Art for his advice, wise counsel, and leadership. In the process-systems area, he has further contributed to its growth by influencing the hiring of Erik Ydstie and Steinar Hauan. Moreover, the department continues to remain young and active largely through Art's example and leadership.

ART'S INFLUENCE IN EDUCATION

Art has creatively integrated the discovery of design concepts, modeling strategies, and process synthesis approaches into both undergraduate and graduate teaching. His approach has been to motivate and to teach through concrete examples. This presents a clear need for new methods and exposes the important features of the problem as well as open research questions that need to be addressed. Art's teaching incorporates fundamental concepts for design and synthesis, with less emphasis on specific computer tools than on a general understanding of what needs to be done. Nevertheless, novel modeling features of his research (including prototypes of ASCEND) have been incorporated into both undergraduate and graduate courses.

Heading a diverse team of researchers (engineers, computer scientists, and even artists), Art has spent the last decade molding these ideas into the n-dim system in order to support the 'design' of the design process for a project team.

Moreover, Art's teaching legacy is evidenced in two texts: the widely distributed work on process simulation (Westerberg, A.W., H.P. Hutchison, R.L. Motard and P. Winter, *Process Flowsheeting*, Cambridge University Press, Cambridge, England, 1979) and the recent design text (Biegler, L.T., I.E. Grossmann, and A.W. Westerberg, *Systematic Methods of Chemical Process Design,* Prentice-Hall, Englewood Cliffs, NJ, 1997)

Finally, Art's legacy as a graduate mentor can be seen in the education of thirty-seven PhD students; six of them have pursued academic careers (see Table 1). Needless to say, he has strong links with all of his former students and they view him as an example of outstanding scholarship.

ART'S INFLUENCE IN THE PROFESSION

Aside from being an intellectual leader of process systems engineering and contributing to research and education, Art has been influential in the chemical engineering profession itself. He has been active in the AIChE, serving on a number of committees (*e.g.* CAST Division, Awards) and teaching short courses. He was one of the founders of CACHE, and he co-chaired the second conference on Foundations of Computer-Aided Process Design, a meeting that now takes place every five years. He was also a member of the National Research Council Committee on Chemical Engineering Frontiers, heading the panel on Process and Control Engineering.

Art has given a large number of seminars in chemical engineering departments, many of them named lectureships. He also serves as member of the editorial board on several journals (*I&EC Research, Computers and Chem.Eng., Chem.Eng. Reviews, AI-Edam, Research in Engineering Design, JOTA*) as well as on the visiting committees at Florida, Princeton, and Wisconsin. His interactions with industry have also been extensive, both in consulting and research projects.

ART AT HOME

Art's pioneering efforts in research and education have not left him isolated from the finer things of life. He and his wife of thirty-five years, Barbara, share a love of music and are frequent visitors to the Pittsburgh Symphony. Moreover, Barbara, an accomplished oboist and pianist (trained at Oberlin College and the University of Florida) organizes annual musical soirees that have enlivened and enriched the lives of many of their colleagues at CMU.

Art and Barbara's sons, Ken and Karl, are continuing in Art's footsteps, with a PhD in chemical engineering (University of Washington) for Ken and a PhD in Physics (Princeton) for Karl. Both maintain strong connections to chemical engineering and are pursuing careers in mathematical modeling and design.

Art remains active in athletics. He is an avid skier and a competitive racketball player. Moreover, his interest in personal electronic devices is legendary among his friends. This can be traced back to his mastery of sophisticated, multiscale slide rules as a teenager, as well as to the purchase of a mechanical calculator for his fraternity house when he was an undergraduate. More recently, Art has awed his colleagues with his expertise on palmtop computers as well as software and sophisticated operating systems for truly individualized computing.

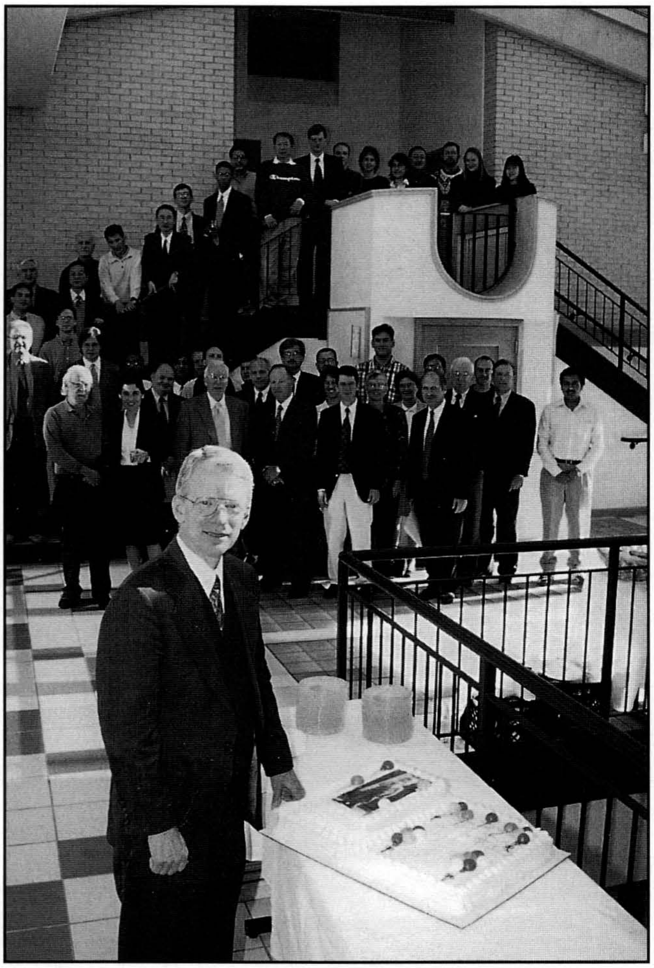
CONCLUSIONS AND A NEW BEGINNING

When Art turned sixty last fall, it dawned on many of his colleagues that the birthday marked a milestone not only in Art's career but also in the evolution of process systems engineering as a major research area in chemical engineer-

TABLE 2

Mini-Symposium Program
Art Westerberg's 60th Birthday
Carnegie Mellon, November 24, 1998

9:00 AM	*An Overview of Art Westerberg's Contributions* George Stephanopoulos, MIT
9:40 AM	*A Further Contribution from Art Westerberg* Karl Westerberg, Princeton
9:55 AM	*Art Westerberg's Work in Process Flowsheeting* Rodolphe L. Motard, Washington University
10:15 AM	*Art's Contributions in DRC and EDRC* Steven Fenves, Carnegie Mellon University
10:35 AM	BREAK
10:55 AM	*ASCEND* Benjamin Allan, Sandia National Lab
11:15 AM	*SPLIT* Oliver Wahnschafft, ASPEN Technology
11:35 AM	*n-dim* Eswaran Subrahmanian, Carnegie Mellon University
12:00 PM	LUNCH
1:00 PM	*Polymer Flow* Andrew N. Hrymak, McMaster University
1:30 PM	*Remarks from a Former Colleague* Fritz Prinz, Stanford University
1:45 PM	*Remarks from Former Dean* Herbert Toor, Carnegie Mellon University
2:00 PM	*Closing Remarks* Ignacio E. Grossmann, John L. Anderson



Colleagues, friends, and former students who joined Art for his surprise 60th birthday celebration and symposium at Carnegie Mellon.

ing. The event was marked with a memorable celebration at CMU—a complete surprise to Art. Along with a gathering of his colleagues, friends, and former students from far and wide, the event included a symposium sponsored by the Chemical Engineering Department. As shown in Table 2, participants included former students, collaborating authors, and researchers as well as colleagues at CMU.

This milestone represents not only Art's legacy but also a continuation of an exciting research area. Our hope is that Art will actively participate in the continued evolution of the area for many years to come. Therefore for all of Art's contributions in

- Defining the core of process systems engineering
- Testing the boundaries of the definition
- Enriching our approaches
- Expanding the scope with a multi-disciplinary context,

and in serving as a

- Profound Analyst
- Creative Synthesist
- Teacher par Excellence
- Challenging and Inspiring Advisor and Mentor
- Innovative Founder
- Excitable Hacker
- And Valued Colleague

we acknowledge a debt of gratitude. For those that have come know him, Process Systems Engineering will always be at the state of the Art.

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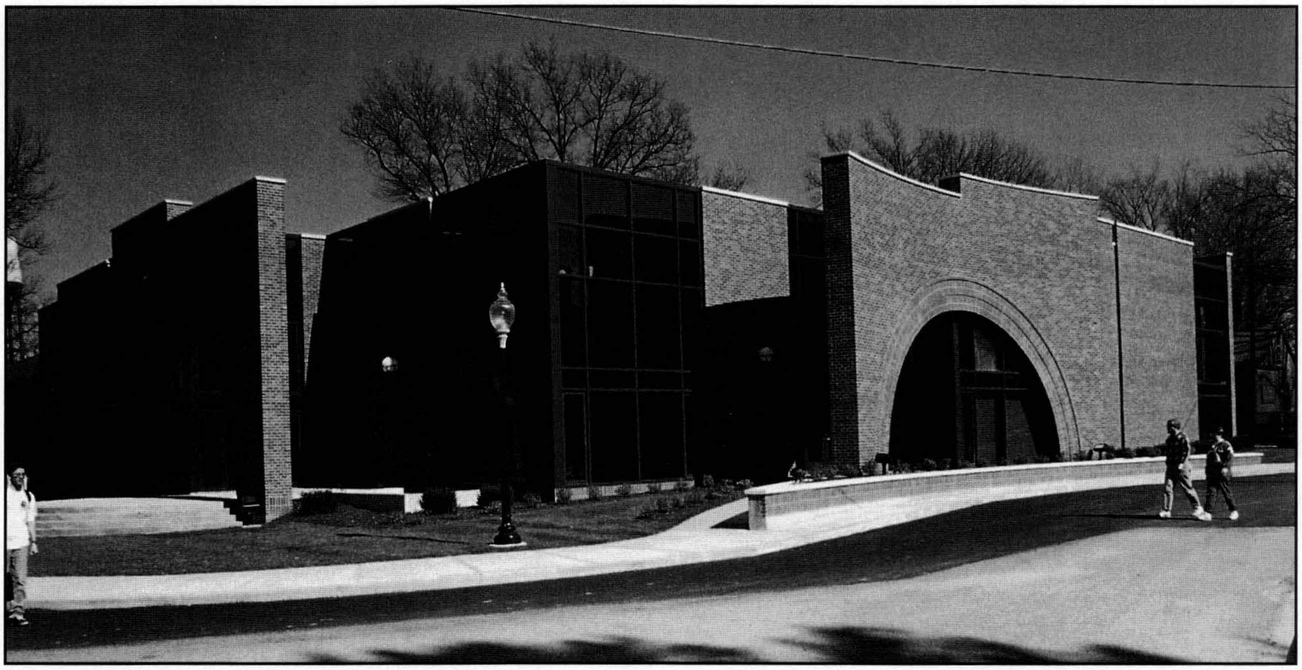
1. Sargent, R.W.H., and A.W. Westerberg, "'SPEED-UP' in Chemical Engineering Design," Trans. Instn. Chem. Engrs, Vol 42, T190-T197 (1964).
2. Nishida, N., G. Stephanopoulos, and A.W. Westerberg, "A Review of Process Synthesis," AIChE J (Journal Review), 27(3), 321-351 (1981) ❐



The Chemical Engineering Department at Rose-Hulman Institute of Technology.

Rose-Hulman Institute of Technology

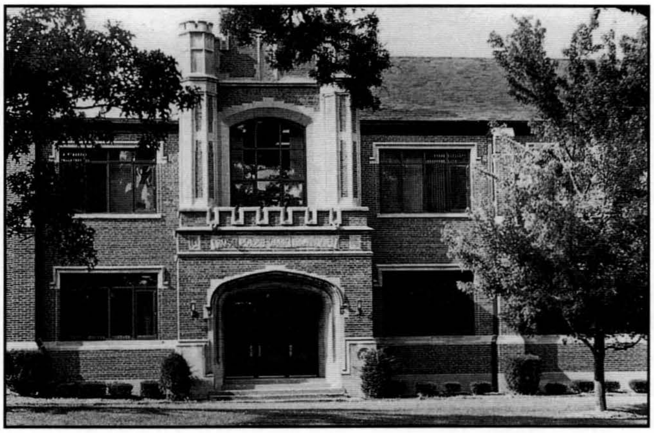
Jerry Caskey, Hossein Hariri
Rose-Hulman Institute of Technology • Terre Haute, Indiana 47803

Rose-Hulman Institute of Technology is one of the few private colleges for undergraduate engineering, mathematics, and science in the United States. It has earned its reputation as one of the nation's leading independent colleges because of its educational philosophy focusing on small classes, dedicated faculty, and an innovative curriculum, all supported by modern educational facilities. The campus is located in a suburban area about five miles east of Terre Haute in west-central Indiana.

The college's 1998 freshman class had a combined SAT average of 1350, with half of the students having achieved 700 or better on the math portion of the standardized test. More than 90% of the students at Rose-Hulman graduated in the top fifth of their high school class. Fall enrollment in 1998 was 1,749 students.

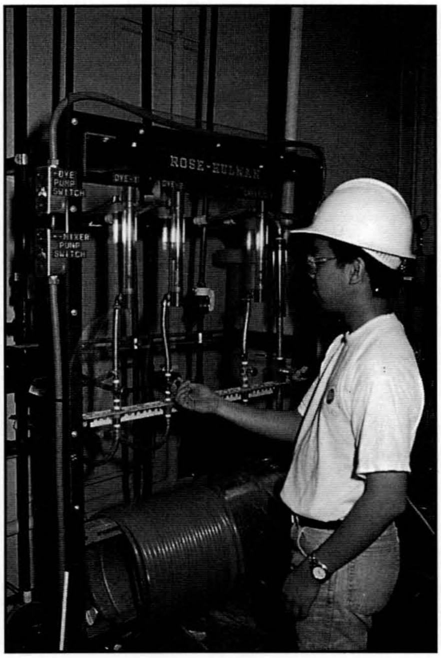
Undergraduate degrees are awarded in applied optics, chemical engineering, chemistry, civil engineering, computer engineering, computer science, electrical engineering, economics, mathematics, mechanical engineering, and physics. Master's degrees can be earned in biomedical, chemical, civil, electrical, environmental, and mechanical engineering as well as in applied optics and engineering management.

There is also an engineering management graduate program designed to help engineers who want to enhance



their management skills for use in technology-based businesses.

Rose-Hulman prides itself on offering outstanding personal attention to the needs of its students, which is illustrated by our 12-to-1 student-to-faculty ratio. Rose-Hulman has been honored in the prestigious Hesburgh Award competition that recognizes a select group of colleges for exceptional efforts to improve undergraduate education.



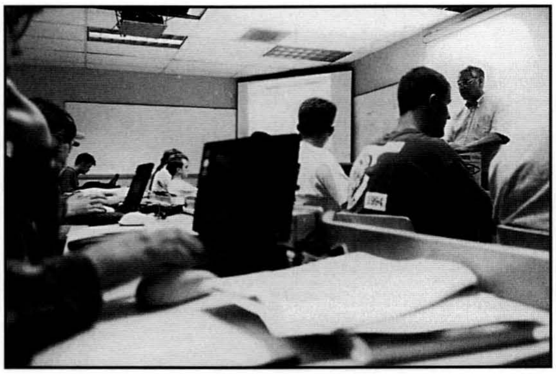
The college's 1998 freshman class had a combined SAT average of 1350, with half of the students having achieved 700 or better on the math portion of the standardized test. More than 90% of the students at Rose-Hulman graduated in the top fifth of their high school class.

Faculty have been innovators in the use of computer-aided instruction and in developing ways to improve the freshman curriculum. In 1995, the Institute was among the first colleges to require all new students to purchase laptop computers.

Special programs offer Rose-Hulman faculty and students an opportunity to work as teams and to use the latest technology to help business and industry create new products, processes, and services. The Technology and Entrepreneurial Development program is creating a model for project-based engineering and science education. The program increases the number of students and faculty involved in industry-sponsored, projects-based programs and creates new laboratories for product and process development.

Rose-Hulman offers a unique commitment to the humanities within an engineering, mathematics, and science curriculum. Students can earn a minor in East Asian Studies, and they are offered language courses in Spanish, German, and Japanese.

During the 1998-99 academic year, Rose-Hulman is celebrating the 125th anniversary of its founding. The college was known as Rose Polytechnic Institute from the time it was founded in 1874 until 1971, when the name was changed to Rose-Hulman Institute of Technology in recognition of more than 100 years of support by the Hulman family. In the fall of 1995, Rose-Hulman became a coeducational campus, ending its 121-year history as an all-male institution.



Top Photograph: *A view of the Rose-Hulman campus.*
Center Photograph: *Tubular flow reactor in the unit ops lab high-bay area (senior student, Thu Vu Pham).*
Bottom Photograph: *Classroom scene showing students using laptop computers.*

CHEMICAL ENGINEERING AT ROSE-HULMAN

It has been reported that the nation's first four-year curriculum in chemical engineering was announced by M.I.T. in 1888.[1] But, "Professor Hammond presented a paper on 'Promotion of Engineering Education in the Past Forty Years' at the fortieth anniversary meeting of the Society for the Promotion of Engineering Education. In this paper, Professor Hammond stated that after searching the early records and catalogues, it did seem that Rose Polytechnic had actually had the first chemical engineering graduate in the United States."[2] Walter Brown Wiley entered Rose Polytechnic in September 1885 and graduated from the Chemical Department in 1889.[3] "Mr. Wiley is the first graduate in the chemical course from the Rose Polytechnic Institute and has been engaged in a special line of work in connection with fuel engineering, especially to improve the quality of coke and the investigation of coking coals."[3]

Rose-Hulman prides itself on offering outstanding personal attention to the needs of its students, which is illustrated by our 12-to-1 student-to-faculty ratio. . . . We will continue to maintain a strong teaching commitment and to give personal attention to students.

The Chemical Engineering Department is the third largest department at Rose-Hulman, with approximately 250 students at the present time.

According to Dr. Warren Bowden, there were sixteen to eighteen undergraduates per class and three graduate students when he joined the department in 1956. The laboratory provided basic experiments in the areas of filtration, evaporation, distillation, and heat transfer. The equipment was old, rusty, and in marginal working order, which made it difficult for students to obtain meaningful data from their experiments. The courses were demanding. Textbooks such as Brown's *Unit Operations* and Weber and Meisner's *Thermodynamics for Chemical Engineers* were used. The students included some extremely talented individuals. For example, the class of 1957 included Ernest Davidson, Glen Miles, and Toby Eubank: Davidson has had a very successful career as a professor of chemistry; Glen Miles obtained a ScD at MIT and had a successful career in industry; and Toby Eubank received a PhD at Northwestern and has been a professor of chemical engineering at Texas A&M University for many years. These students did not get sheepskin diplomas since Rose Poly switched to paper diplomas in the late 1920s.

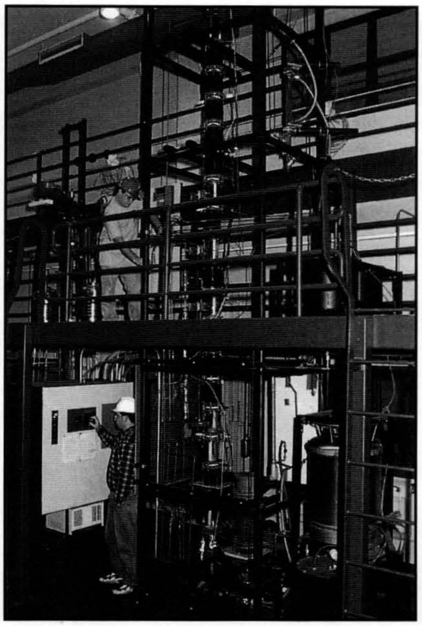
The department went through a period of low student enrollment during the early and mid '60s. Then, in 1966, Dr. Sam C. Hite, Chairman of Chemical Engineering at the University of Kentucky, went to lunch with a recruiter for Commercial Solvents, located in Terre Haute, and was told that chemical engineering was about to be discontinued at Rose. He learned that the chairman had already left, and only two professors (Warren Bowden and Tony Blake) remained. Sam was interested, so he applied for and was made chairman of the Department. He immediately began a drive to increase the faculty from two to eight, the BS ChE degrees from 16 to over 70 per year, and to aggressively find money for new equipment and facilities. The plan began with the recruiting of Dr. Noel E. Moore from Kentucky. Noel later followed Sam as chairman at Rose-Hulman and served as chair until 1997, when he stepped down to prepare for his retirement in 1998. Hossein Hariri is the current chairman of the Department.

RECENT CHANGES AND DEVELOPMENTS

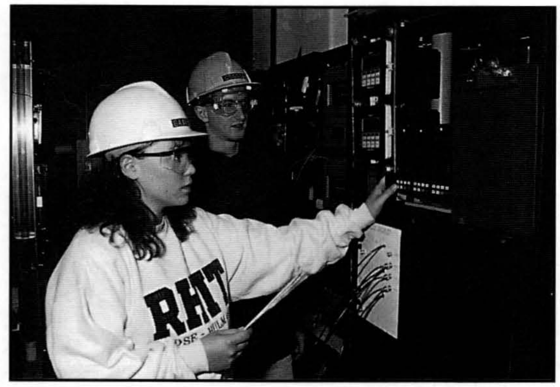
There have been evolutionary changes at Rose-Hulman and in its Chemical Engineering Department. Historically, the Institute has perceived a constant need to restructure and renew curricula and has sought the necessary equipment and encouraged faculty to develop new curricular materials based on the availability of additional resources. This cycle of discovery, initiation, acquisition, dissemination, and integration is one of the Institute's greatest strengths. The relatively small size of the Institute, the dedication of its faculty, and its outstanding student body make Rose-Hulman a recognized leader in curricular innovation in undergraduate engineering, science, and mathematics education.

Approximately one-quarter of the incoming freshmen participate in the Integrated First-Year Curriculum in Science Engineering and Mathematics. In a 12-credit "super course" during each quarter of the freshman year, students receive instruction in calculus, physics, chemistry, computer science, engineering graphics, and engineering design in a block-scheduled sequence of carefully coordinated activities that emphasize the interrelationships between the disciplines. Students receive a single grade for the course each quarter.

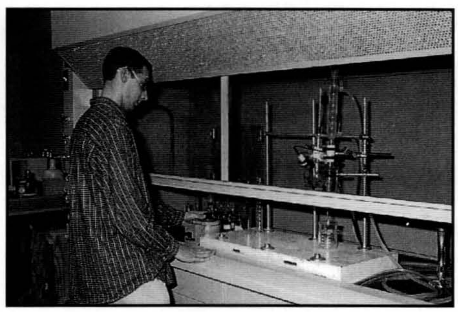
A central component of this course is an array of quarterly projects developed by teams comprised of three or four students. The following is a partial list of projects chosen by students in the spring quarter of the 1997-98 academic year: writing a program for Windows-based scheduling of final



◄ *Senior students Joe Lathey and Bill Morphew shown with the Corning Distillation Column in the Unit Operations Laboratory high-bay area.*



▲ *Seniors Amy Gainey and Jeremy Conner hard at work on a process control experiment in the Unit Operations Laboratory low-bay area.*



◄ *The Unit Operations Laboratory occupies a high- and a low-bay area as well as three separate rooms. Junior Craig Clark works with the Othmer Still Unit in one of the separate labs.*

exams; devising a method for determining the speed of a fast-moving object whose trajectory is not known; devising and carrying out an original experiment using a wind tunnel of the group's own design; investigating how variations of reactant ratio affect the properties of the plastic you create; synthesizing a ferrofluid and purifying it to improve performance. At the end of each quarter, students present their projects in a large poster session open to all faculty and students at the Institute.

One notable characteristic of Rose-Hulman is an interest in laboratory experiences for the students and a teaching emphasis leaning toward the practical side of the practical-theoretical spectrum. "If football teams were coached the way engineering students are educated, the players would all sit on the bench reading the play book," says Dr. Sam Hulbert, Rose-Hulman President.

Academic programs that implement our vision of student research and engineering design and discovery activities occur both in departmental courses and interdisciplinary activities. In the case of the engineering disciplines, such activities are generically known as "project work."

Project-based education was a key recommendation of the Task Force on Design and Research of the Commission on the Future of Rose-Hulman. The Commission is a national 410-member group of volunteers from business and industry. It developed 105 recommendations to help Rose-Hulman maintain its engineering and science educational leadership into the 21st century. In order to implement the recommendations of the Commission on the Future, the number of industry-based projects must be significantly increased, specifically those that benefit from multidisciplinary expertise applied to industrial projects. Some of these projects could be used as freshman design projects or as senior engineering-design projects, or as graduate thesis projects. It is our intent that each and every Rose-Hulman student should have a project-based experience.

Until recently, the only type of project work involving undergraduate students in a significant way has been coursework projects. They are projects done by a student or a student team, with the team managed solely by the students, as an academic exercise for academic credit. The faculty member is not part of the team. On the other hand, R&D projects are done by a team composed of undergraduate students in addition to faculty members.

The U.S. Department of Energy has awarded Rose-Hulman a $6.7 million grant to construct a 35,000 sq. ft. John T. Myers Center for Technological Research with Industry. This two-story facility will provide 7,500 sq. ft. of floor space dedicated to the W.M. Keck Foundation Laboratories for Research with Industry. An additional 10,000 sq. ft. will be dedicated to flexible laboratory space to support student research projects. Electronics and mechanical shops, a presentation room, conference room, and administrative offices will complete the facility.

As part of engineering design in the Chemical Engineering Department, undergraduate student project teams have worked on a number of industrially sponsored projects. One example is working in conjunction with Siemens Automotive to develop a non-pyrotechnic test to authenticate simulations and steady-state tests in plastic manifolds.

The mission of the Department is to provide a balanced education that will enable our students to practice as professionals in the dynamic industrial environment, to appreciate their responsibility to and respect for their colleagues, and to become life-long learners.

UNIT OPERATIONS LABORATORY

The Unit Operations Laboratory has a long history of being an integral part of the undergraduate chemical engineering program. This is in keeping with the conviction that students learn best by doing. In 1984, the Department moved into a new building that was constructed with funds donated by the Olin Foundation. The faculty designed the new facilities around the Unit Operations Laboratory, and some existing equipment was moved from the old laboratory, but for the most part new pilot-plant-size projects were built in the new laboratory. One piece of equipment that was brought over from the old laboratory (affectionately referred to as the "Dungeon") was the Sperry filter press. A forklift was rented for the move, but when it was time to connect the piping, it was discovered it had been set with the wrong end facing the supply tank. Not to be deterred, Professor Caskey promptly went to the football practice field (this was in August) and commandeered several hefty linemen and some steel bars. They hoisted the filter press, turned it 180 degrees, and returned to the football field. This type of family atmosphere continues to be one of the strengths of Rose-Hulman.

The laboratory has been continuously updated and now boasts over twenty different experimental modules for unit operations lab projects. These modules include distillation, gas absorption, liquid extraction, drying, filtration, microfiltration, membrane separations, mixing, heat exchangers of several types (including boiling and condensation), vapor-liquid equilibria, gas and liquid fluid flow, pumps, cooling towers, kinetics (including fermentation), process control, and other miscellaneous modules.

The laboratory has been operated as a project lab as opposed to a "cookbook" lab. In some cases, projects are assigned that require data to be taken for scale up. This has worked well with boiling heat transfer, cooling towers, filtration, drying, and membrane separations. Operating the laboratory in this fashion requires a large commitment from the faculty, and in any given quarter five of the eight full-time faculty are involved in the laboratory. Oral reports have also been an integral part of the laboratory. Each lab group of three gives three oral reports that are critiqued by other groups, and faculty are present at all oral reports to "grill" the group. This again requires a hefty commitment of time from the faculty. The reward comes when students call back after graduation and report they are able to hold their own when asked to report orally on a job assignment.

The Department also recognizes process control as an industrially important area that our students need to understand. The Camille Computer company has provided three laboratory/pilot-scale PC-based control systems that have been integrated with the lab projects. Our main Corning glass distillation column, ceramic cross-flow microfiltration unit, and process-control pilot plant unit are fully instrumented and are linked to the Camille systems. The systems have been designed to also operate in manual mode in the event of an unexpected sensor/transmitter fault or a "student-mediated event" that makes automatic control impossible. Foxboro 761 controllers are also a part of the process control pilot plant, allowing students to gain experience with remote local controllers as well as the PC-based systems.

COURSE PROJECTS

In addition to the lab projects, most elective courses also feature projects. For example, the environmental unit operations course has a project where the students make drinking water from raw sewage, using the operations of sedimentation, granular filtration, activated carbon adsorption, deionization, and microfiltration. The students conduct tests to determine the water's purity after each unit operation. This hands-on project reinforces the subjects studied in class. The students are invited to make coffee or hot chocolate from the final water—the ultimate test if they believe the process really works. In the polymer engineering course, students choose a plastic product and analyze it by one or more of the techniques studied in class. During the part of the course where polymer processing is studied, groups experimentally measure the amount of a characterized polyethylene from an extruder and compare the amount extruded to the amount predicted by the equations studied in class.

A number of required courses also have projects associated with them. Our first contact with students enrolled in chemical engineering is in the freshman year in a course titled "Introduction to Design." The objectives of this course are twofold: to give the students a better understanding of chemical engineering and what chemical engineers do, and to give the students insight into the reason for, and the importance of, subsequent courses in the curriculum. To accomplish these objectives, the students are given a process patent along with relevant design data and are asked to do a preliminary design and economic analysis for a plant using the process. The students work in groups of three, with the professor serving as their supervisor/consultant. The students do the necessary material and energy balances, size selected items of equipment, determine the equipment cost and the total capital investment required, and determine the total product cost and the return on investment. Obviously, the process must not be complex, and close supervision and guidance is required. While the students feel that a lot is demanded of them in the course, they also feel that it is worthwhile and accomplishes its objectives.

In the sophomore year, students take a two-quarter sequence in material and energy balances. The capstone of this sequence is a case-study project done in teams of three completing a material and energy balance over a process supplied to each team. Students are given assistance through information on the course web page. They learn engineering methods in solving a case-study problem and are able to improve their computer skills as well as their skill in writing reports.[4]

Our materials engineering course has for some years required student teams to participate in a poster presentation, and the teams now have the option to develop a web page on some aspect of materials. Projects are also a requirement in the air pollution control course. The most ambitious project in this course was the work of a group that exposed pregnant rats to varying doses of sulfur dioxide and then examined the offspring for evidence of damage to internal organs.

CURRICULAR INTEGRATION

Rose-Hulman has placed increasing emphasis on curricular integration. As mentioned previously, about 25% of the freshmen take a program that emphasizes interrelationships between disciplines. The mechanical and electrical engineering departments have continued this trend into the sophomore year, emphasizing the common principles of conservation—conservation of charge, energy, mass, and momentum.

The chemical engineering department restructured the sophomore material and energy balance sequence to include this same emphasis. The restructured courses will be offered in the fall of 1999 and are titled "Conservation Principles and Balances" and "Basic Chemical Process Calculations." The first course includes an introduction to engineering calculations, application of numerical techniques, concepts of systems, conservation, and accounting of extensive properties (mass, energy, charge, linear, and angular momentum) as a common framework for engineering analysis and modeling. The second course offers the application of conservation of mass and energy in analysis of chemical engineering processes including recycle, bypass, and multi-stream processes as well as methodologies used by practicing chemical engineers. The use of computer software, especially spreadsheets, is highly integrated into the course.

The Department has also developed another tool to emphasize the interrelationships of the sophomore-, junior-, and senior-required chemical engineering courses. This is a CD-ROM developed by Professor Caskey using a saturate gas plant from Marathon's refinery in Robinson, Illinois. Modules have been made for material and energy balances, fluid mechanics, heat transfer, thermodynamics, mass transfer, and process design. This CD-ROM provides a resource for linking subjects regardless of the textbook or teaching method used in any particular course. A student can perform a material balance of a multicomponent absorption column in material balances (in the sophomore year), complete a vapor/liquid calculation on the same column in thermodynamics (in the junior year), find heat loss from the column in heat transfer (in the junior year), and calculate the number of stages required in mass transfer (in the senior year). Students can use this tool to get a sense of how courses are interconnected.

THE FUTURE

The Department faculty roster went through a change last year when three new faces replaced faculty members who were retiring. Mentoring and passing on the experience and tradition of the Department to the new faculty members are now important tasks that lie ahead. We will continue to maintain a strong teaching commitment and to give personal attention to students. The mission of the Department is to provide a balanced education that will enable our students to practice as professionals in the dynamic industrial environment, to appreciate their responsibility to and respect for their colleagues, and to become life-long learners.

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We extend our appreciation to Joseph Shaeiwitz (West Virginia University) for acting as Guest Editor in compiling, reviewing, and editing the following papers that comprise a special-feature section on outcomes assessment in this issue.

Commentary . . .

OUTCOMES ASSESSMENT

Its Time Has Come

Teaching is no longer sufficient; student learning must be demonstrated.

JOSEPH A. SHAEIWITZ
West Virginia University • Morgantown, WV 26506-6102

When faced with the necessity of developing an assessment plan for regional accreditation about seven years ago, my initial response was directly from the "textbook of faculty responses when confronted with doing something new." I was not enthusiastic about having another task to fit into an already-full schedule.

If you have the same attitude, or if you are faced with a colleague reciting all of the "textbook responses" as excuses for not doing outcomes assessment, consider this: all faculty members reading this article have been doing outcomes assessment for their entire careers. When mentoring graduate students, the goal is to develop a set of skills to permit the MS or PhD to do research on any topic; the mentor (consciously or unconsciously) constantly compares the student's acquired skills to the desired skills and focuses on making certain that all of the desired skills are acquired before a degree is granted. Assessing undergraduates involves the same process—plus the additional challenge of dealing with a larger number of students.

The concept of outcomes assessment has been around for about thirty years. It is becoming more prevalent in higher education because of its acceptance by regional accreditation agencies and by professional accreditation agencies such as ABET, and because of the demand for more accountability by boards of trustees and state legislatures.

***Joseph A. Shaeiwitz** received his degrees in Chemical Engineering from the University of Delaware (BS, 1974) and Carnegie Mellon University (MS, 1976; PhD, 1978). He is curently Associate Professor of Chemical Engineering at West Virginia University. His research interests are in design, design education, and outcomes assessment. He is coauthor of the text* Analysis, Synthesis, and Design of Chemical Processes, *published in 1998 by Prentice Hall.*

With the adoption of EC 2000, engineering programs are struggling with how to develop meaningful assessment plans. The following collection of papers is designed to assist with the development of those plans. The papers contain opinions and observations from those involved on both sides of the first few EC 2000 pilot visits in chemical engineering, those involved in educating engineers on outcomes assessment, and those who have experience in developing and implementing assessment strategies for courses and curricula that can serve as models for other assessment plans.

Some may wonder why we should be doing outcomes assessment. After all, if our students graduate and get good jobs or attend graduate or professional school, we are doing fine. Right? But are employers really satisfied with the skills of the graduates they hire? Are students really satisfied with the education they received? Do graduates really possess the knowledge and skills faculty believe they possess?

How do we know the answers to these questions?

Outcomes assessment allows faculty to begin to answer them. With outcomes assessment, teaching is no longer just the act of showing up in class and simply giving lectures, assignments, and exams. Teaching now includes setting goals for student learning in a course and/or curriculum, and taking responsibility for students achieving those goals. Teaching now involves determining those goals in consultation with constituencies such as employers and students. The curriculum being taught should now have opportunities for development of desired skills over time. Teaching now involves evaluating whether students have achieved the desired skills and knowledge and modifying courses and curricula to ensure that the goals are achieved (continuous quality improvement). Teaching is now based on an output model, *i.e.,* measuring the knowledge and skills of the graduate and the student moving through the curriculum, not on an input model where the output is assumed based solely on curriculum content. Teaching is no longer sufficient; student learning must be demonstrated.

Among the results of implementation of an assessment plan are faculty who know their students—who know their students' individual strengths and weaknesses and who are in a position to help individual students exploit those strengths and overcome those weaknesses. In recent years, we have heard several of the most prestigious research universities proclaim publicly that they plan to devote more time to undergraduate education. Outcomes assessment provides them with the perfect opportunity to make good on their promise.

In recent years, we have heard several of the most prestigious research universities proclaim publicly that they plan to devote more time to undergraduate education. Outcomes assessment provides them with the perfect opportunity to make good on their promise.

If we agree that the skills and knowledge that students obtain in the curriculum are what is being assessed, the next question is how to do such an assessment. This requires an assessment plan with three main elements. First, goals must be set, preferably in consultation with external constituencies. A subset of enumerating goals is to determine performance, *i.e.,* what a student must do to achieve a goal. Second, multiple measures of achievement of these goals are necessary. Among the most common measures are interviews with students, alumni and employer questionnaires, portfolios, and capstone projects. Finally, the results obtained from these measures must be used to improve the educational process.

The papers that follow describe assessment plans that all use the methodology described above, but each illustrates a different set of measures. A valid assessment plan need not and should not contain all of the elements of all of the plans described in these papers. Over-assessing is as bad as under-assessing.

Another key question is: When should assessment be done in the curriculum? The answer is: At multiple points within and beyond the curriculum. Graduates should be tracked to obtain a self-evaluation of their education. Employers should be surveyed to obtain an evaluation of their employees' education. Students about to graduate should be assessed (self-evaluation and faculty evaluation) to determine whether they have achieved the desired outcomes.

Students in the curriculum should also be assessed to determine if mid-course corrections are needed. Assessment can be done in a single course, as described in one of the papers that follows, or classroom assessment can be done to determine the outcomes of a single class.[1]

Finally, who should do the assessment? It is tempting to say "all faculty." While that would be an ideal situation, it may be unrealistic—although all faculty teaching undergraduate classes really should be involved with the undergraduate assessment plan. It is important, however, to avoid the opposite extreme! Assessment cannot be the job of one faculty member, or even worse, solely the job of an external consultant. There must be a critical mass of faculty involved in the assessment process to ensure its continuity and to ensure that all parts of the curriculum are covered.

So, now you are enthusiastic about assessment! And, after reading the following papers, you will want to learn even more about it. Where do you go? One place is to the Best Assessment Processes in Engineering Education conference held at Rose-Hulman Institute of Technology. Another is to a web page that I have created (found at http://www.cemr.wvu.edu/~wwwche/outcome/index.html) that includes the assessment references I have found most enlightening.

It should be noted that many faculty are uncomfortable with outcomes assessment, especially using it for accreditation purposes. We have become comfortable with the much-maligned "bean counting" process. As noted in several of the following papers, creating and implementing an assessment plan involves finding one good solution to an ill-defined problem. At the design level, that is what we as engineers are trained to do. So, by implementing an assessment plan, we are simply demonstrating to our students that we can solve the type of problem we expect them to solve in the capstone course.

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RE-ENGINEERING ENGINEERING EDUCATION

CHEMICAL ENGINEERING AND ABET EC 2000

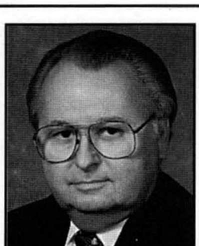
STAN PROCTOR, ABET PAST PRESIDENT
DICK SEAGRAVE, EAC PAST CHAIR
Iowa State University • Ames, IA 50011-2230

Adoption of ABET Engineering Criteria 2000 by the Accreditation Board for Engineering and Technology, along with a revised set of Program Criteria for Chemical Engineering by AIChE, will certainly have a significant effect on the education of chemical engineering graduates as we move into the 21st century. There is a profound shift in emphasis, from requiring a specified curricular content to evaluation of programs for the success they demonstrate in meeting their own goals for how and how well they prepare their graduates. This, along with how well programs continuously assess and improve their processes to achieve these goals, is a major "sea change" for engineering accreditation. A concomitant increase in flexibility, which should allow chemical engineering programs significant latitude in meeting their objectives, is perceived by many, particularly those in industry and in higher academic administration, as being long overdue. There is, however, a significant price to be paid.

For the first time in three decades, many chemical engineering programs are now thinking carefully about the goals and execution of their undergraduate curricula. The typical curriculum that has been in place since the 1960s, an amalgam of our petroleum- and industrial-commodity-chemistry based past and the transport-phenomena revolution of the 1960s, now faces new challenges. An increasing number of our graduates find employment in the biologically based industries (food, textiles, agricultural byproducts, pharmaceuticals, biomedical industries) and in the information-processing industries (microchip manufacturing, solid-state processing, software development). Many graduates find employment as financial analysts, seek careers in law and medicine, and embark, as engineers, on a wide variety of career paths. The faculty in charge of undergraduate curricula, who have put their trust in a prescribed and somewhat narrow set of courses (usually organic and physical chemistry, fluid mechanics, heat and mass transfer, chemical reactor design, thermodynamics, process control, and design) are now beginning to think seriously about the role of subjects such as biology, solid-state chemistry and physics, new materials, nanotechnology and mega-systems, etc., as they relate to their goals for their graduates. They are becoming more concerned about how elements of the curriculum fit together and support each other in the educational process.

ABET Engineering Criteria 2000 attempts to provide a framework by which chemical engineering faculty members can develop their programs to achieve these desirable evolutionary changes without jeopardizing their accreditation standing, while at the same time requiring them to change their emphasis from what is taught to what is learned. This is no small feat. The new criteria essentially requires that chemical engineering programs address three basic questions:

- *Within the context of chemical engineering, what are your objectives for your graduates, and how did you and your constituencies set them?*
- *How do you determine if your objectives are being met?*
- *What are you doing to fix things if your objectives are not being met, or improve things even if they are?*



***Stanley I. Proctor** received his BSChE, MS, and DSc in chemical engineering from Washington University. He is a past president of ABET, a past president (and Fellow) of AIChE, and has recently been named chair of AIChE's new Career & Education Operating council. Since his retirement in 1993 he has been in private consulting.*

Richard C. Seagrave is currently a Distinguished Professor of Chemical Engineering and Interim Provost at Iowa State University. He is a past chair of the Engineering Accreditation Commission of ABET and is vice-chair of AIChE's Career and Operating council. He is also an AIChE Fellow. (Photograph not available.)

After a considerable amount of discussion and public input, the Engineering Accreditation Commission agreed on a basic set of attributes (outcomes) which should be required of all engineering graduates. This list of 11 attributes (a through k from Criteria 3) forms the minimum "experience base" that the profession accepts as necessary attributes (or outcomes) for all engineering graduates. It is expected that individual programs will supplement this list, which is not intended to be exhaustive.

The challenge provided by Engineering Criteria 2000 for programs to evolve in meeting their goals is also an opportunity. Those faculties who felt constrained by ABET in the past now have an opportunity to experiment.

The "knowledge base" that is required by the general criteria for all engineering graduates has been considerably modified in the new criteria. For example, neither courses in physics nor chemistry are specifically required. Specification of a minimum amount of social sciences and humanities courses is no longer stated. The appropriate coursework will still need to be prescribed by the faculty, with an eye towards fulfilling the attributes stated in EC 2000 and the program criteria, consistent with the overall goals of their program and the nature of their discipline.

AIChE, through its representatives on the Education and Accreditation Committee, has taken a conservative approach in proposing its new outcomes-based program criteria. The current state of these criteria, as well as other items of interest regarding the new process, may be monitored on the World Wide Web at http://www.abet.org. Note that the language addresses the requirements placed on the capabilities of the graduates. No courses are specifically required. Perhaps the most significant change is the discontinuance of the requirement of one-half year of advanced chemistry, which has been replaced by a more demanding requirement of a thorough grounding in advanced chemistry, in a list of areas of chemistry which may be specified more precisely by the faculty itself in any program. For many years, there has been the conventional and wide-spread belief that either ABET or AIChE "required" both organic and physical chemistry, although this has never been the case. Chemical engineering faculties throughout the country have locked themselves into this box. It will be interesting to see, now that the box has been unlocked, what choices will be made.

Unquestionably, the greatest area of concern that has been expressed among chemical engineering faculty and department chairs has been an uncertainty with respect to "what does ABET expect of us in the areas of outcomes assessment and continuous improvement?" The short answer, we believe, is that programs will need to set their own expectations in this area, as well as in other areas. Actually, they always have. In a profession that has placed the principles of process control in a central place in its curricula, it should not be difficult to adapt the basic principles of measurement, feedback, set-points, and load changes, to determining the degree to which their graduates are meeting their objectives. The public, of course, expects this.

To aid faculty and administrators in this area, as well as to gain experience in the new accreditation process, a series of pilot visits has been completed. In the 1996-97 academic year, two institutions, the University of Arkansas and Worcester Polytechnic Institute, were visited using EC 2000. In the 1997-98 academic year, three more institutions, Harvey Mudd College, The Georgia Institute of Technology, and Union College were evaluated using EC 2000. One result of these pilot studies will be a set of case studies that should be useful in helping to set goals, in establishing mechanisms of outcomes assessment, and in preparing for and participating in accreditation visits. These studies are not intended to be a "how to" set of instructions, but rather a set of examples that have been used successfully. The first case study, for a fictitious institution, Coastal State University, is now available on the ABET Web site at http://www.abet.org. It represents an amalgamation of experiences from the pilot studies.

In addition, the Engineering Accreditation Commission, in concert with the educational elements of the various technical societies, including AIChE, is developing a standard set of training materials for engineering program evaluators. This course will be useful for faculty and administrators in getting a better understanding of the accreditation process that will accompany the new criteria. Also, with the sponsorship of NSF and with the cooperation of industry, a series of twelve regional NSF-sponsored industry-hosted workshops for training faculty from every engineering program in the U. S. began in late 1998 and will continue for the next three years. Watch the ABET Web site for more information.

The challenge provided by Engineering Criteria 2000 for programs to evolve in meeting their goals is also an opportunity. Those faculties who felt constrained by ABET in the past now have an opportunity to experiment. Those institutions whose general accreditation review was scheduled in 1998-99 academic year and is scheduled to occur in the 1999-2000 or 2000-2001 academic years have the choice to seek re-accreditation under either the existing criteria or under EC 2000. All engineering programs at the institution must make the same choice. Beginning in the year 2001-2002, all institutions will come under the new Engineering Criteria 2000. What the future holds will be determined by the experiences we will share during that period. ❐

Outcomes Assessment OPPORTUNITY ON THE WINGS OF DANGER

Gloria Rogers
Rose-Hulman Institute of Technology • Terre Haute, IN 47803-3999

Why would 370 engineering faculty from 150 institutions and four countries travel to Terre Haute, Indiana, in April? No, ski season was over. Actually, it was to attend the first "Best Assessment Processes in Engineering Education" symposium, held on the Rose-Hulman Institute of Technology campus. Response to the symposium is indicative of the degree of interest in learning about assessment techniques that can be applied to engineering education.

It would be wonderful to report that the primary motivation for the interest in assessment is because we are all wildly interested in learning how we can implement continuous quality improvement in our educational programs. Although we *are* interested, we also need to answer to a multitude of demands on our time and resources. In reality, the changes in the accreditation requirements embodied in EC 2000[1] represent a new approach to validation of quality in engineering education and are driving the interest in outcomes assessment. Many agree that EC 2000 is the right and appropriate approach to accreditation. But it also presents several major challenges for each of us.

I have had opportunities to interact with faculty and administrators from various campuses, engineering societies, and ABET. The purpose of this article is to share my observations from the field of assessment and my experience from interacting with those who are working to align their educational processes to be consistent with both the letter and the spirit of EC 2000.

Gloria Rogers *received her BS and MA in Sociology and her PhD in Educational Administration from Indiana State University. She is currently Vice President for Institutional Resources and Assessment at Rose-Hulman Institute of Technology. She is currently working with the Accreditation Board for Engineering and Technology on implementation of EC 2000, and is one of the organizers of the national symposium "Best Assessment Processes in Engineering Education."*

MAJOR CHALLENGES

There are three Chinese characters that make up the English word "challenge": 1) opportunity, 2) on the wings, 3) of danger. I would like to provide what I believe to be the major challenges facing each of us as we move to outcomes assessment. These challenges will highlight both the opportunities and the dangers associated with our transition to EC 2000.

■ *Understanding Assessment and the Continuous Quality Improvement (CQI) Process*

Engineering faculty recognize the importance of the use of models in solving engineering problems. The value that a CQI model contributes is that it gives faculty a common language and a conceptual framework to guide the process.

Opportunity • There are many models that have been developed that depict the CQI process—including the "Two-Loops of EC 2000"[2] and "Assessment for Continuous Quality Improvement"[3] models. I have had engineering faculty share with me copies of CQI models they have developed that represent everything from a chemical process to an electrical circuit. The important thing is that you develop/adapt/adopt a model that is meaningful to you and your program that includes all the elements of the CQI cycle. Development of this framework will provide a common understanding of what the process entails and will guide you as you structure your activities.

Danger • There are really two dangers in development of a model. The first is that all the elements and relationships that are crucial to the CQI process are not included. The minimal elements that need to be illustrated in a model are

- The relationship between your program outcomes and your program and institutional mission
- Student learning outcome goals for your engineering program (broadly stated, not measurable, *e.g.,* communications skills)
- Involvement of constituencies, *i.e.,* where are your constituents involved and what is the nature of their involvement
- Specific performance specifications for each learning outcome (measurable, *e.g.,* demonstrated ability to use correct grammar)
- Educational practices and strategies employed to provide students with the opportunity to gain knowledge, skill, and experience to achieve the desired outcomes
- Collection of evidence (assessment) to determine whether or not the learning outcome has been met
- Evaluation of the evidence, *i.e.,* interpretation of evidence and recommendations for improvement
- Feedback loops, *i.e.,* what is the nature of feedback loops and how is assessment and evaluation information used to improve programs

The second challenge in the development of a model appropriate for your program is that you spend all your time debating the complexity and validity of the model and do not get on with it. Like the CQI processes you will develop, the model itself can be improved as you go through the cycle and learn more about the process and your institutional culture.

■ *Use of Assessment Terminology*

I call this the "Tower of Babel" effect. I recently read an article that described the importance of language and meaning in systems engineering.[4] It described the problems faced when workers with the same goal cannot communicate well enough to accomplish the task before them.

Opportunity • As in the case of scientific notation, the use of terminology in assessment is not standardized. The terms (goals, objectives, criteria, metrics, etc.) are often used differently or interchangeably. This can create confusion and alienation from the CQI process. Development of "Stepping Ahead: An Assessment Plan Development Guide"[5] was created, in part, to address this issue. But when EC 2000 was crafted, the term "objective" was used in the way that the guide uses the term "goal." It is important to note that there is no one right way to define these terms. Each engineering program/college should agree upon term definition and use terms consistently. This provides an opportunity to focus on the meaning of assessment terms and will, in the long run, clarify the process and serve the program well. Table 1 demonstrates assessment term definitions[5] with examples. It is not meant to be exhaustive of all possible combinations or examples.

Danger • The most significant danger is that there will be no attempt to develop a common assessment language among the key players and the process will fall apart due to confusion and frustration. Different members of the community may have strong preferences for term definition because of their experiences. Listen carefully and bring closure on this issue early in the process. There will be lots of battles to be fought during the process—this is not one of them. Agree to agree and move on. Then use the terminology consistently—and often.

■ *Development of Performance Criteria*

Development of specific, measurable performance criteria is probably the most challenging—and important—step in this process. Most of us can begin with EC 2000, Criterion 3 (the eleven desirable attributes of the engineering graduate), to develop our student outcome objectives (goals?). These are broadly stated, however, and cannot be measured. The challenge of each engineering program is to define what is meant by each of the objectives. We think we know when students demonstrate the ability to communicate effectively, but when faculty begin to spell out what they mean, they find there is not always a clear consensus. In addition, if we value "effective" communication skills, we need to tell students what characteristics should be present in order for them to

TABLE 1
Definitions of Assessment Terms

Term	Definition	Other Terms Used	Example
Goal	A statement describing a broad outcome; not measurable	Objective Outcome	Graduating students will be effective team members.
Objective	Statement(s) derived from the goal that define the circumstances by which it will be known if the desired change has occurred; not measurable	Goal Outcome	When engaged in a dialogue with team members, or as part of a small group project, students will perform effectively as team members.
Performance Criterion	Specific, measurable statement identifying performance required to meet the objective. The performance criteria must be confirmable through evidence. Objectives may have multiple criteria.	Outcomes Standards Specifications	1. Initiate and maintain task-oriented dialog. 2. Work for constructive conflict resolution. 3. Strive for meaningful group consensus. 4. Support other team members in the effective performance of their roles. 5. Initiate and participate in group maintenance activities

demonstrate such skills. We also need to provide students with opportunities to learn, develop, and demonstrate the skills, and give them feedback on their progress. For this to happen, we need to develop measurable performance criteria that give precision to the objective.

Opportunity • The exercise of developing measurable performance criteria will provide faculty with a shared understanding of the desired outcome. It will also promote discussion about strategies that can be implemented to give students the experiences they need to be able to demonstrate the outcome. The criteria that are developed will also shape the assessment method and enable faculty to develop assessment processes that are clearly linked to the desired outcome.

Danger • This is a component of the CQI process that is often left out. It is common for the assessment planners to move from listing objectives to choosing assessment methods. This is understandable because the development of measurable criteria is painstaking—critical, but painstaking. This is where common sense must prevail. Continuing with the "effective communications skills" example, it would be possible to develop fifteen or more very well-defined performance criteria for effective communications skill. If you look at all of your learning objectives (fifteen or more?) and each of them has ten or more performance criteria, the overall assessment task becomes overwhelming. Start with as many performance criteria as you can think of for each learning objective and prioritize them in order of importance. The final number chosen should include those criteria that are considered to be critical to the objective and still make the assessment task manageable.

■ *Use of Local Resources*

Recently, I heard an engineer say, "We engineers find it hard to believe that we can learn anything from someone who is not an engineer!" Although this was said in jest (I hope), there seems to be a reluctance to go outside engineering circles to ask for help in designing and/or implementing the CQI process as it relates to education.

Opportunity • It is important to capitalize on your local resources. Many regional accreditation agencies have moved to an outcomes-assessment-based accreditation process for the institution. The likelihood of there already being someone on your campus who is charged with the responsibility to do outcomes assessment is very great. Find them and begin a dialog about how what they are doing at the institutional level can inform and assist your program-assessment efforts. It would also be very unusual if you did not already have resources on your campus that could provide assistance in areas of educational assessment design (College of Education, Educational Psychology, etc.), data collection (Institutional Research, Registrar, Admissions, Student Affairs, etc.), and statistical analysis of social science data (Social Sciences, Business, etc.). Identifying local resources and engaging them in the planning and implementation process will provide both an economy of effort and a perspective external to the engineering program. This is bound to strengthen the overall quality of your assessment efforts.

Danger • There is a real danger that engineering faculty and administrators will adopt the attitude that no one outside of engineering can possibly understand the complexity and demanding curricula that embody the engineering discipline. It is important to remember that what you are looking for here are "worker" bees, not the queen. There are others outside of engineering who can help you think through the design of your assessment plan, ask the right questions, and collect and analyze the data. It is the primary purpose of the engineering faculty and administrators to give the plan substance, evaluate the results, make recommendations based on the evaluation, and implement the improvement. All the other steps can be done in consultation with others.

■ *Hiring An "Expert" To Do It For You*

There are many resources available to you from within higher education. People who are knowledgeable and experienced in assessment and evaluation processes are available to support you in your efforts.

Opportunity • A critical element in satisfying the requirements set forth in EC 2000 is to educate yourself in the assessment and CQI processes as they relate to educational programs. Having "experts" provide professional development activities for faculty is a good way to get the process started with a common language and understanding. If you have no local resources, seeking consultation from outside the college could be very beneficial.

Danger • There is a temptation to hire someone with expertise in assessment to do assessment for you (or, "to" you). Although having someone on the staff to assist in the process would be advantageous, there is a danger that others would expect him or her to develop and implement the plan. The appropriate role of an assessment specialist on the staff would be to guide the process and work with faculty to develop and validate *their* assessment plan. Determining responsibility for collection and analysis of data should be done in consultation with engineering faculty and administration. Evaluation of assessment results is more appropriately done by the faculty. Faculty should then recommend changes for improvement in the engineering program based on their evaluation of the assessment results.

■ *Student Involvement*

We must never forget that all of this is about improving the quality of student outcomes. It is designed to prepare students for careers and lifelong learning. As the focus of this effort, we need to find ways to involve students in the assessment of their own learning outcomes.

Opportunity • As learning objectives are moved from the abstract to the concrete through development of specific, measurable performance criteria, students will have opportunities to assess their own skills in ways that are meaningful to them. For example, the use of peer assessment when students are asked to give oral reports will not only provide opportunities for them to assess each other, but will also reinforce the characteristics that are important for oral communication to the student who is making the assessment. The feedback being given to students making the reports will help them know where they need to make improvements. This can be done within the context of an engineering class.

Danger • The process of assessment for continuous quality improvement is designed to help us improve our engineering programs. We cannot forget that we can only improve our programs if we improve the educational outcomes for *individual* students. There is a danger that they will be left out of the process. Statistics are the impersonal representation of a collection of personal experiences of individual students. Let us accept the challenge of getting them involved in the assessment of themselves and their peers. Who knows? This act alone may be the most significant improvement in our programs and have the greatest impact on student outcomes.

It is time to take advantage of the lessons learned from those who have been engaged in outcomes assessment in different contexts and apply them to engineering education. . . . we can take advantage of the opportunities provided by the new approach to accreditation to assess our programs as a whole.

The dangers in doing so can be avoided if we are willing to learn from others who have been there.

■ ***"One Size Fits All" Mentality***

The assessment process is like the engineering design process in many ways. One of the most significant ways is that it is a process that is ambiguous—there is no *one* right answer. Some answers are better than others, and some answers are definitely wrong.

Opportunity • Although CQI models can provide a good starting point, development of an assessment plan should reflect the uniqueness of your institution, your student body, and your program. The move to outcomes assessment requires conversations about who you are and what outcomes you want for your students—not someone else's students, institution, or program. These conversations should contribute to shared definitions and understandings that will enhance the overall educational experience for students and faculty alike.

Danger • Because of the sense of urgency that we all feel to get moving on the development of our assessment plans and data collection, there is a danger that we will try to impose someone else's framework or methods to our own program. There is a real risk in this approach because of the lack of personal buy-in from the people who are going to be responsible for implementation, evaluation, recommendations, and improvements—your faculty. Again, reviewing the work of others is very positive. There will also be things that you will be able to adapt/adopt for use on your campus, but those decisions need to be made *after* you have developed a clear understanding of your learning outcomes objectives and performance criteria for your program. Not until you reach these understandings will you be able to determine what methods will best fit your program.

WILL EC 2000 SURVIVE?

The long-term impact of EC 2000 will depend on several factors. As I have talked to engineering faculty from around the country, I have found mixed emotions about whether or not the changes will bring about real, significant improvement in the way engineering education is delivered and the quality of learning outcomes for students. I believe there are four elements critical to the successful transition to EC 2000.

1. Faculty must believe that EC 2000 will promote student learning and not be adverse to their own academic agenda.

Many faculty agree that EC 2000 is the "right" thing to do. They are in general agreement that the previous criteria were too restrictive and irrelevant to the changing nature of the engineering profession. But EC 2000 represents a radical, untested departure from what was a familiar and "comfortable" process—although unpleasant. The new approach to accreditation will take time and energy before any "payoff" will be seen. Even where EC 2000 is embraced, faculty want to know what they will have to give up in order to comply with the requirements. Unless they can see the long-term, beneficial results of their efforts, it will be difficult to get their buy-in.

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USING PORTFOLIOS TO ASSESS A ChE PROGRAM

BARBARA M. OLDS, RONALD L. MILLER
Colorado School of Mines • Golden, CO 80401

At the Colorado School of Mines (CSM), we have been assessing students outcomes (both in the core and in the major) for over a decade. From the beginning, we chose to use portfolios as the major component of our assessment plan. In this paper, we will briefly describe the history of our assessment program, sketch the assessment process that we use, list the advantages and disadvantages of portfolios, and then focus on the use of portfolios as a major instrument of chemical engineering program assessment and evaluation.

BRIEF HISTORY OF ASSESSMENT AT CSM

During the late 1980s, the Colorado legislature (like those in many other states) became interested in higher-educational accountability and assessment and passed legislation requiring the Colorado Commission on Higher Education to "develop an accountability policy and report annually on its implementation." Colorado allowed each institution to develop an individual assessment plan appropriate for its size, student body, mission, and goals. CSM chose to develop a *portfolio* assessment plan, for which we have now been collecting and evaluating data since 1988.

***Barbara M. Olds** is Principal Tutor of the McBride Honors Program in Public Affairs for Engineers and Professor of Liberal Arts and International Studies at the Colorado School of Mines, where she has taught for the past fifteen years. She is chair of CSM's assessment committee and has given numerous workshops and presentations on assessment in engineering education.*

***Ronald L. Miller** is Associate Professor of Chemical Engineering and Petroleum Refining at the Colorado School of Mines, where he has taught chemical engineering and interdisciplinary courses and conducted research in educational methods for thirteen years. He is chair of the Chemical Engineering Department Assessment Committee and acting chair of the CSM Assessment Committee.*

Of course, over the past decade there have been a variety of external drivers for assessment in addition to legislatures, including the total quality management model in industry, regional accrediting agencies (North Central in our case), and most recently, ABET Engineering Criteria 2000 (EC 2000). Colorado, like many other states, has recently begun to emphasize performance indicators rather than assessment programs for accountability, so our assessment focus at CSM has shifted to satisfying our own internal needs for continuous improvement and to providing evaluation information to external constituencies, including ABET. Since ABET accredits programs rather than institutions, our assessment focus has become more diffuse, shifting to departments—but we continue to use portfolio assessment to measure CSM core curriculum outcomes, and several of our programs (including chemical engineering) are building on the existing portfolio plan in developing their individual assessment processes.

For the institution-wide portion of our assessment plan, a random sample of incoming students is selected each year (approximately ten percent of the first-year class) for whom we develop portfolios. We collect typical quantitative data for each student, such as SAT and ACT scores and GPAs. In addition, we include in the portfolios samples of classroom work from a variety of courses as well as surveys and other feedback on the students' satisfaction with the institution. Each spring, the portfolios are evaluated by a campus-wide assessment committee. Results from the assessment/evaluation process are fed back to the campus community as a whole as well as to other constituent groups.[1,2]

ASSESSMENT PROCESS

We have learned over the years that it is extremely important to develop and improve an assessment *process* with clearly delineated steps. Several helpful guides to developing an assessment plan exist (most notably those by Rogers and Sando[3] and the National Science Foundation,[4]), but we have found that a process based on answering the questions summarized in Table 1 has been most helpful for our needs.[5] By answering the questions iteratively, we can be assured that we have not overlooked any important components of our assessment plan.

Such a process does not dictate that a particular assessment method be used, but it does help faculty decide which methods are most appropriate for measuring certain outcomes. While we are focusing on the use of portfolios in this paper, we recognize that a variety of other assessment methods will also yield valuable results.

...a portfolio [is] a collection of student work over time ... Many types of materials can be collected, including papers, reports, projects, oral presentation tapes, homework, exams, and self-assessments.

TABLE 1
Program Assessment Matrix

Goals	What are the overall goals of the program? How do they complement insitutional and accreditation expectations?
Educational Objectives	What are the program's education objectives? What should your students know and be able to do?
Performance Criteria	How will you know the objectives have been met? What level of performance meets each objective?
Implementation Strategies	How will the objectives be met? What program activities (curricular and co-curricular) help you to meet each objective?
Evaluation Methods	What assessment methods will you use to collect data? How will you interpret and evaluate the data?
Timeline	When will you measure?
Feedback	Who needs to know the results? How can you convince them the objectives were met? How can you improve your program and your assessment process?

PORTFOLIO OVERVIEW

Pat Hutchings defines a portfolio as a collection of student work over time (*e.g.*, a semester, a college career) for purposes ranging from student advising to program evaluation.[6] Many types of materials can be collected, including papers, reports, projects, oral presentation tapes, homework, exams, and self-assessments. Portfolios can be kept by students, department advisors, or institutional assessment offices. As electronic portfolios (a web-based system of student work products allowing for on-line access and evaluation) become more widely used, the possibilities will continue to increase.[7]

Portfolios, like all assessment instruments, have strengths and weaknesses. Some of the key advantages of portfolios cited by Prus and Johnson[8] include:

- *They can be used to view learning and development longitudinally (e.g., samples of student writing over time can be collected), which is a most valid and useful perspective.*
- *Multiple components of a curriculum can be measured (e.g., writing, critical thinking, research skills) at the same time.*
- *The process of reviewing and grading portfolios provides an excellent opportunity for faculty exchange and development, discussion of curriculum goals and objectives, review of grading criteria, and program feedback.*
- *They can increase student participation (e.g., selection, revision, evaluation) in the assessment process.*

At the same time, portfolio assessment raises several significant issues, including:[8]

- *Portfolio assessment is costly in terms of evaluator time and effort.*
- *Management of the collection and grading process, including establishment of reliable and valid grading criteria, is likely to be challenging.*
- *Security concerns about storage of student work must be addressed and managed.*

To help alleviate these concerns, Prus and Johnson make the following recommendations:[8]

- *Consider portfolio submission as part of a course requirement, especially a "capstone course" at the end of a program.*
- *Use portfolios from representative samples of students rather than having all students participate.*
- *Provide training for raters.*

Prus and Johnson's "bottom line" on portfolios is that they are potentially very valuable for adding important "longitudinal and 'quantitative' data, in a more natural way," and that they are "especially good for multiple-objective assessment," such as the kind required for ABET EC 2000 compliance.

PORTFOLIOS AS PART OF AN ASSESSMENT PLAN

The Chemical Engineering Department at CSM is the second largest in the school, with over 400 majors. It has relied on portfolio assessment for many years, but has recently undertaken extensive revision of its assessment plan based on careful application of the steps in the assessment process listed in Table 1 and lessons learned from the legislatively mandated program of the past decade. The plan discussed in this paper is still in the early stages of development, testing, and implementation, but it represents the current thinking of the chemical engineering faculty. By focusing on ABET EC 2000, especially the student outcomes description in Criterion 3, by obtaining input from industry, alumni, students, and faculty, and by participating in a number of institution-wide and departmental discussions and workshops, the faculty developed three primary goals for the chemical engineering program:

- *Instill in chemical engineering students a high-quality basic education in chemical engineering fundamentals.*
- *Develop in chemical engineering students the skills required to apply chemical engineering fundamentals to the analysis, synthesis, and evaluation of chemical engineering processes and systems.*
- *Foster personal development in chemical engineering students to ensure a lifetime of professional success and an appreciation for the ethical and societal responsibilities of a chemical engineer.*

The faculty then developed from three to six measurable educational objectives (what students should know and be able to do) for each goal. Table 2 lists a small sampling of the objectives that were developed and indicates how each objective maps onto ABET student outcomes.

Once the faculty agreed on program goals and educational objectives, they began to identify curricular and co-curricular opportunities for students to achieve each objective. As part of this work, an implementation matrix was developed to indicate which educational objectives were addressed in each course in the ChE curriculum. Table 3 includes a small portion of the matrix as an example. Working together to complete the entire matrix, the faculty were able to identify overlaps and areas of little or no coverage and to begin a discussion on how to enhance weak areas. In the table, an "X" denotes that one or more of the learning objectives in a particular course addresses the indicated departmental educational objective. A completed matrix for the entire curriculum will also indicate that achieving many of the educational objectives requires work over several courses and semesters.

Once goals and objectives were drafted and the implementation matrix indicated that all of the objectives were addressed within the ChE curriculum, the faculty began to consider evaluation methods that would be appropriate for measuring each objective. While they ultimately settled on a number of methods, including senior exit interviews and alumni surveys (triangulation, or the use of multiple measures, is usually considered the best approach to meaningful

Do not forget to assess and improve the portfolio assessment process itself. Few of us will get it right the first time, so revision and refinement is essential.

TABLE 2
Example Educational Objective for Each Departmental Goal

Goal	Educational Objective
Instill in students a high-quality basic education in chemical engineering fundamentals.	Graduates will be able to apply knowledge of unit operations to the identification, formulation, and solution of chemical engineering problems (ABET Criteria 3a and 3e).
Develop in students the skills required to apply chemical engineering fundamentals to the analysis, synthesis, and evaluation of chemical engineering processes and systems.	Graduates will be able to design and conduct experiments of chemical engineering processes or systems and they will be able to analyze and interpret data from chemical engineering experiments (ABET Criterion 3b).
Foster in students personal development to ensure a lifetime of professional success and an appreciation for the ethical and societal responsibilities of a chemical engineer.	Graduates will demonstrate an ability to communicate effectively in writing (ABET Criterion 3g).

TABLE 3
Portion of Implementation Matrix

	Mass & Energy Balances	Fluid Mechanics	Unit Ops Lab	Senior Design
Apply knowledge of rate and equilibrium processes	X	X	X	X
Apply knowledge of unit operations		X	X	X
Design a process or system			X	X
Function on a team			X	X
Effectively communicate orally and in writing			X	X
Use engineering tools	X	X	X	X

assessment), they agreed to continue to collect and assess portfolios for a representative sample (approximately 20%) of their majors. They also decided that it was best to be selective in deciding what to collect in the portfolio, making a single item serve multiple needs whenever possible. As a result, for example, all three of the objectives listed in Table 2 can be assessed by evaluating written reports collected from the student's unit operations laboratory course. Other student work products that will be collected include final exams from junior- and senior-level courses (*e.g.,* fluid mechanics, heat transfer, mass transfer, and kinetics), and written reports from senior design courses.

Collecting material for the portfolio is only the beginning of the assessment process, however. Next, faculty had to decide what constitutes evidence that students met each objective and how the evidence would be evaluated. They decided on a set of performance criteria, *e.g.,* 100% of students in unit operations lab will be rated at 2 (apprentice), 3 (proficient), or 4 (exemplary) on their ability to apply knowledge of unit operations for each open-ended laboratory report included in the portfolio. The percentage is an estimate at this point and will have to be refined as the assessment plan is put into place and tested.

Faculty next needed concrete, articulated levels of performance against which to measure student achievement. Thus, they developed scoring rubrics for each objective, using a process recommended by Pickett:[9]

1. *Determine learning objectives*
2. *Keep it short and simple*
3. *Each rubric item should focus on a different skill*
4. *Focus on how students develop and express their learning*
5. *Evaluate only measurable criteria*
6. *The entire rubric should fit on one sheet of paper*
7. *Reevaluate the rubric (Did it work? Was it sufficiently detailed?)*

Table 4 shows a sample rubric for assessing unit operations laboratory reports based on the objectives listed in Table 2. Note that the department chose to include only four levels of student performance (exemplary, proficient, apprentice, and novice) that were deemed adequate for the purpose of program assessment. Rubrics using the same four performance levels have been developed for each item of student work collected in the portfolio.

Once each academic year's portfolio materials have been

TABLE 4
Scoring Rubric for Assessing Unit Operations Laboratory Reports

Objective	*4 - Exemplary*	*3 - Proficient*	*2 - Apprentice*	*1 - Novice*	*Score*
ChE graduates will be able to apply knowledge of unit operations to the identification formulation, and solution of ChE problems	Student groups apply knowledge with virtually no conceptual or procedural errors affecting the quality of the experimental results.	Students groups apply knowledge with no significant conceptual errors and only minor procedural errors.	Student groups apply knowledge with occasional conceptual errors and only minor procedural errors.	Student groups make significant conceptual and/or procedural errors affecting the quality of the experimental results.	
ChE graduates will be able to design and conduct experiments of ChE processes or systems and they will be able to analyze and interpret data from chemical engineering experiments.	Student groups design and conduct unit operations experiments with virtually no errors; analysis and interpretation of results exceed requirements of experiment and demonstrate significant higher-order thinking ability.	Student groups design and conduct experiments with virtually no errors; analysis and interpretation of results meet requirements of experiment and demonstrate some higher-order thinking ability.	Student groups design and conduct experiment with no significant errors; results are analyzed but not interpreted; very limited evidence of higher-order thinking ability.	Students groups design and conduct experiments with major conceptual and/or procedural errors; no evidence of significant analysis and interpretation of results; fail to meet requirements of the experiment; demonstrate only lower-level thinking ability.	
ChE graduates will demonstrate an ability to communicate effecively in writing.	Written report is virtually error-free, presents results and analysis logically, is well organized and easy to read, contains high-quality graphics, and articulates interpretation of results beyond requirements of the experiment.	Written report presents results and analysis logically, is well organized and easy to read, contains high-quality graphics, contains few minor grammatical and rhetorical errors, and articulates interpretation of results that meet requirements of the experiment.	Written report is generally well-written but contains some grammatical, rhetorical, and/or organizational errors; analysis of results is mentioned but not fully developed.	Written report does not present results clearly, is poorly organized, and/or contains major grammatical and rhetorical errors; fails to articulate analysis of results meeting requirements of the experiment.	

collected, the departmental assessment committee meets to review and refine the language of each rubric. Sample student work is used to test the updated rubrics and to ensure that committee members' scores are "normed" prior to scoring the collected portfolio materials. This procedure ensures that valid assessment data can be obtained using each rubric and that inter-rater reliability is assured.

Finally, the information obtained from the assessment and evaluation process is fed back to the chemical engineering department students and faculty as well as to other interested stakeholders, including employers and the departmental external advisory committee. The faculty considers assessment results from each year in planning revisions to the curriculum. In addition, the process itself is critiqued annually and changes are made based on stakeholder feedback. In brief, the process and the product will both undergo continuous review and improvement.

LESSONS LEARNED

Based on a decade of portfolio assessment at CSM, we have learned many lessons; the most important and relevant ones are:

- *Avoid the temptation to start collecting portfolio materials before developing clear goals, objectives, and an assessment process. Before decisions are made about which materials to collect and assess, be sure to answer questions about what is being assessed, how the data will be analyzed, when materials will be collected, and who will receive the results.*
- *Be sure to promote stakeholder buy-in by involving as many constituencies as possible in the portfolio development and implementation process. If one lone faculty or staff member is assigned the assessment task, the plan will almost assuredly fail.*
- *Look for campus resources to help faculty get started with portfolio assessment and provide faculty development opportunities. Most schools have some level of assessment expertise on campus—do not be afraid to search for help in training engineering faculty to become good portfolio assessors.*
- *Remember that quality of results is more important than quantity. Portfolio assessment does not have to measure every learning objective in every course in the curriculum. Collect results that will be of most value in improving the learning and teaching process and use sampling techniques to collect a longitudinal snapshot of student achievement.*
- *Allay fears in colleagues who view portfolio assessment as a "touchy-feely" process by including them in the development of well-designed scoring rubrics and inter-rater reliability testing.*
- *Do not forget to assess and improve the portfolio assessment process itself. Few of us will get it right the first time, so revision and refinement is essential.*

CONCLUSIONS

Portfolio assessment is a potentially robust method for evaluating chemical engineering programs and meeting ABET EC 2000 requirements. As with any assessment instrument, however, successful use of portfolios requires careful implementation of an assessment process based on developing measurable objectives with articulated performance criteria, identifying curricular and co-curricular activities designed to help students meet each objective, collecting and evaluating assessment data using well-developed scoring rubrics, and providing assessment results to all interested stakeholders in the process.

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Opportunity on the Wings of Danger

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2. Administrators will need to expend resources to meet the requirements and have confidence that the resources expended will have sufficient benefit to the overall program.

Many engineering programs are already hampered by the demands for limited resources—money, equipment, space, time. etc. Deans and department heads need to make decisions about how to balance limited resources. The need to develop a culture of assessment for continuous quality improvement processes does not come without costs. If the move to EC 2000 is not see as having a defensible cost/benefit ratio in relation to other critical needs, there will be resistance to support the effort at a level that will be sufficient for success.

3. There needs to be an attitude of trust and cooperation among faculty and between faculty and administrative staff.

In the mind of a faculty member, there is a thin line between evaluating the program and evaluating "me." Administrators need to be trusted not to use program-assessment information to evaluate individual faculty members. The issue of evaluating a faculty member must be done outside the context of program evaluation to maintain faculty confidence in the process. In addition, faculty need to be trusted to use the assessment information to enhance student learning.

4. EC 2000 evaluators must understand assessment and CQI and know adequate processes when they see them.

There are at least three things that can happen when the EC 2000 evaluators come to your campus. **1)** They will be well versed in EC 2000 and have a clear understanding of the requirements, limitations, and possibilities for developing and implementing CQI and assessment processes in engineering education. As a result, they will be able to assist you in evaluating your program and make recommendations for improving your educational processes based on sound assessment information. **2)** They will not have a very good understanding of the requirements, limitations, and possibilities for developing and implementing CQI and assessments processes in engineering education. As a result, they will not be able to assist you in improving your processes, and because you have done your homework, you will end up educating them. **3)** They will not have a very good understanding of the requirements, limitations, and possibilities for developing and implementing CQI and assessment processes in engineering education—but they do not know it. As a result, they will apply inappropriate standards to the processes you have developed.

Scenarios 2 and 3 are outcomes that will erode the good that EC 2000 can bring to engineering education. Of course, the horror stories will travel much faster (and be more exaggerated) than the success stories.

The good news is that the Engineering Accreditation Commission is working very hard at providing training sessions for all EC 2000 evaluators. During this process, they are involving evaluators in discussion of the elements of assessment planning and CQI processes. Information about the availability of training sessions can be found on the ABET web site.[6]

CONCLUSION

While there are many dangers that lie ahead for engineering programs that are implementing outcomes assessment, there are none that cannot be overcome by careful preparation and planning. The industry and education representatives of ABET's Engineering Accreditation Commission (EAC) are taking the lead by providing programs to better inform evaluators and engineering faculty of the core concepts and processes embedded in EC 2000. It is important to remember that few of us have more to lose if EC 2000 fails than those who have had the courage to step forward to develop, propose, and champion the new accreditation criteria—the EAC. This activity has been in response to the deafening outcry of engineering faculty to do away with the rigid, "bean-counting" criteria that previously existed.

It is time to take advantage of the lessons learned from those who have been engaged in outcomes assessment in different contexts and apply them to engineering education. Faculty are already doing outcomes assessment in the classroom, and we can take advantage of the opportunities provided by the new approach to accreditation to assess our programs as a whole. The dangers in doing so can be avoided if we are willing to learn from others who have been there.

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OUTCOMES ASSESSMENT
An Unstable Process?

DAVID DIBIASIO
Worcester Polytechnic Institute • Worcester, MA 01609

The new outcomes-based world of higher education and accreditation may be scary to some, annoying to others, fun to a few, but certainly challenging to all of us. We are faced with examining our educational process in new ways, optimizing a complex ill-defined process, and presenting it clearly and coherently to our accreditation agency. The goals of this paper are to outline the basics of outcomes assessment, describe a format useful for assessment preparation, summarize some lessons learned from the 1996 pilot visit conducted at Worcester Polytechnic Institute (WPI), and discuss some consequences of outcomes assessment.

Let's start with the question, "Why do assessment?" A number of responses come to mind, such as "I do it to assign grades," "...to make accreditation agencies happy," "...to make grant funders happy," "...to know that what I do as an instructor is meaningful," "...to know that students are learning what I set out to teach them."[1] If we care at all about our teaching, we each embrace one or more of these during any course we teach. But how many of us examine the complete curriculum or spend significant time with colleagues (and not just our chemical engineering colleagues) discussing and *doing something constructive* about these issues? Until recently, I suspect, such faculty and departments were in the small minority.

So, is there a problem? We have been successfully educating competent engineers for decades. Why change? I like the simple answer—we can always do better and are ethically obligated to strive for the best. There are many ways to improve teaching and learning, and outcomes assessment is one of them. Others may prefer the more involved response that links rapidly changing technological market forces to needed changes in our graduates' abilities.[2] Either way, future graduates must function effectively in multidisciplinary teams, communicate well, understand global and societal issues related to engineering, and of course, master engineering and scientific fundamentals. A rigorous, well-designed assessment process can make that happen, allow new flexibility in the curriculum, and result in continuous improvement. I am hard pressed to find a reason why we should not do it. We should be aware there are costs associated with doing it right, however.

***David DiBiasio** has taught in the Chemical Engineering Department at Worcester Polytechnic Institute since 1980, and had industrial experience at the DuPont Company prior to that. His current interests are in biological reactor engineering, engineering education, and educational assessment.*

ASSESSMENT BASICS

Assessment basics are relatively simple: define objectives, determine if students are meeting them, and improve the educational process if they are not. An excellent primer is provided by Rogers and Sando,[3] and other articles in this issue expand on these principles. The assessment process usually includes

- Setting educational objectives
- Determining performance criteria
- Defining practices
- Defining assessment methods
- Evaluating the assessment data
- Feeding back the results to improve the curriculum

Measurable outcomes are linked to objectives, and the whole process drives continuous improvement of the educational system. Sounds straightforward, right? Well, maybe not. Goal setting and determining performance levels for chemical engineering topics may not sound too bad, but what about these "assessment methods"? Experts tell us we need methodologies that are both formative and summative.

Formative methods are those that take place periodically during a course or curriculum and answer the question, "Is it working?" For example, a mid-course survey might tell a professor some on-line course adjustments are needed. Summative methods take place at the end and answer the question, "Did it work?" A comprehensive final exam tells the professor what fraction of the students mastered the material at specified comprehension levels.

Either method might involve qualitative or quantitative tools. Simply put, quantitative tools involve numbers such as exam scores, survey results, and database analysis. Qualitative tools involve textual or verbal information, including open-ended survey responses, videotape data, and interview transcripts. The same experts tell us that we should use both types for formative and summative evaluations, and that triangulation, redundant measurements with multiple independent tools, is very important.

Most of us are comfortable with quantitative data, but many engineers are uncomfortable with qualitative data. We may not know how to collect it or analyze it properly, and too often it is regarded with disdain. Any mention of "discourse analysis" may set off the touchy-feely alarm in many engineers. But some of the richest and most meaningful data from an educational experience are sometimes obtained only through qualitative analysis. Several of the items in ABET EC 2000 Criterion 3 are quite well suited to measurement using qualitative techniques.

Process Control Analogy

The best assessment processes include a mix of methods and tools. The process is also closed-loop since it contains an essential feedback step that forces us to correct the curriculum when we detect problems in the outcomes. It is hard to ignore the analogy to process control, and other authors have used block diagrams to help simplify the description.[4] I believe the analogy and diagrams are also useful to make a different point.[5]

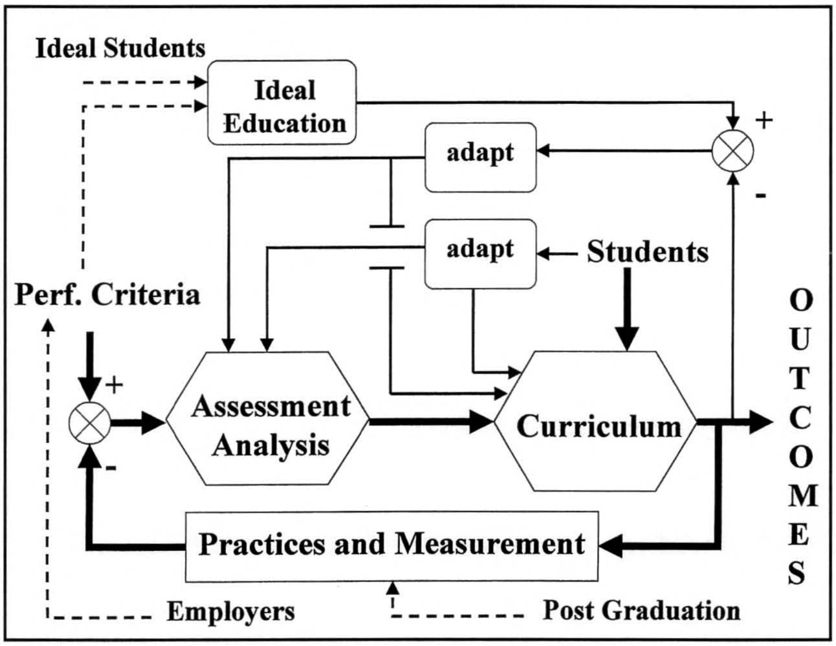

Figure 1. *The assessment process as a multiloop feedback control system.*

Figure 1 presents one general view of assessment. The primary loop is shown in bold. The "process" is the curriculum into which students enter. They exit possessing desired abilities or outcomes. The output is measured by having students demonstrate these abilities through defined practices. Feedback is achieved by comparing measured outcomes against the "set point" or performance criteria for each outcome. The controller is the assessment analysis that dictates changes in the curriculum when outcomes don't meet performance criteria. Unfortunately, this is a multivariable, multiloop system with difficult measurements. If we wanted all students to graduate with red hair, then measurement, feedback and correction would be easy. Our goals include some tough-to-measure qualities, however, such as lifelong learning and understanding of ethics and social issues.[4]

We also need to consider some measurements taken well after graduation. They tell us something about the connection between our curriculum and job performance. Such measurements must also enter our feedback loop, even though there is a significant time lag. Our constituencies include our students' employers. Since most students take industrial positions, industry involvement in determining objectives and performance criteria is important. This results in set-point disturbances.

The characteristics of students entering college change with time. Why wait until students are well into the curriculum (when it may be too late) to make corrections? Any good control-system designer would try solving this problem with a feedforward loop. Such a loop might include adapting the process and the controller.

Finally, a major goal is "continuous improvement," or optimization. Model-reference adaptive control is one possible scheme. Changing set points/performance criteria are input to an ideal educational model. The theoretical output is compared to our actual outcomes and an adaptation algorithm modifies both the controller and the curriculum appropriately so that the system moves continuously toward the optimum. Maybe such an analogy is a bit unrealistic, but some time-optimal control strategy is needed.

At this point, we have a multivariable, feedback-feedforward, time-optimal control system to design and operate. It is potentially unstable. Variable measurement is difficult, and we have ignored the sampling problem: how often and how many students will be sampled? If we are serious about assessment, then the only conclusion is that this is not an easy problem.[5] It is complex, with many possible solutions—none of which are simple. Recall that multiple types of evaluation tools should be applied at several levels of the curriculum and across appropriate time periods. Assuming none of us have achieved the ideal educational system, we must realize that even the simplest design will include changes in the curriculum. Force fitting of an existing static and inflexible education system to EC 2000 will probably not work.

But chemical engineers are good at attacking and solving difficult, ill-defined, complicated problems. After all, isn't that what we want our students to do? This problem will require some effort to do right, but it can be done, and the results should be well worth our efforts.

If we are serious about assessment, then the only conclusion is that this is not an easy problem. It is complex, with many possible solutions—none of which are simple.

THE WPI VISIT

The Chemical Engineering Department at WPI was accredited under the new EC 2000 during the first pilot evaluation in 1996. We faced the problems described above and are still working on solutions. Our specific preparation and timetable were unique to that pilot experience, but some elements of preparation and presentation might be useful to others.

Visit Preparation

Visit preparation cannot begin early enough, and two years is an absolute minimum for the first visit. Four or five years would be better. It should be clear that departments can no longer wait until the year before a visit to begin preparations. Outcomes assessment is continuous, and data collection and analysis must occur constantly. The educational process has a four-year time constant, so early formative data collection is highly recommended. Also consider that alumni and employer survey data might have little meaning unless collected at the proper time intervals.

Educational objectives must be defined first. Presumably there will be institutional ones and discipline-specific departmental ones. A common mistake is to launch into discussions about assessment methods without clear objectives. It is best that faculty and staff avoid many hours in committee meetings discussing the content and logistics of student portfolios before they understand exactly how portfolios link to objectives. When clear, measurable objectives are in place, the specification of performance criteria and the choice of assessment tools derive logically. This may seem obvious, but experience shows that we tend to digress quickly into discussion of assessment methodologies prior to understanding how we really want to use them.

A committed (compensated) department coordinator can help facilitate the process, but all faculty must be involved. A time commitment level of at least 25% is needed for the coordinator.[6] There is no secret formula for engaging all faculty in the process, but one potentially useful argument is that outcomes-based assessment is being required in more and more research proposals. Proposals with decent assessment plans have the edge over others; hence, research-oriented faculty might gain useful knowledge from participation in the process.

Consultant use is highly recommended, but consultants cannot and should not write the assessment plan. They cannot substitute for the faculty. Faculty must define objectives, performance criteria, and feedback mechanisms. Consultants can help recommend methodologies and assist with data-evaluation strategies.

Documentation Using an Assessment Matrix

Presentation of a complex assessment process to a visiting team is problematic. One must clearly show how the department plan addresses the major evaluation criteria. If student portfolios are used, you cannot expect your evaluator to read through several of them looking for evidence of items under Criterion 3. The portfolio itself needs a guide, probably written by the student, and it needs evaluation, probably by faculty. Our experience, and that of others,[7] showed that the assessment matrix format is quite useful for presenting the department's plan, but much detailed additional documentation must accompany the matrix.

The assessment matrix is one way to help organize the plan. It is concise, and it serves as a guide to additional documentation. I will show how we used it to outline our assessment plan, how two years later it portrays some potential problems, and how it illustrates some consequences of outcomes assessment that are important outside of WPI.

Table 1 shows a portion of the WPI Chemical Engineering Department matrix. The column headings are the general assessment process steps. The row headings are the individual educational objectives. Our department adopted ABET EC 2000 Criterion 3 (a-k) as objectives and we show two of them for example purposes. Some definitions are necessary to follow the matrix:

IQP *The Interactive Qualifying Project. This project is a significant open-ended, non-classroom experience that equals three courses worth of credit. It is usually done during the junior year in teams with students from different majors. It must address a problem that considers the interaction of technology with society and culture. Faculty advisors may be from any discipline, and the project topics are interdisciplinary. Since we believe that the global nature of technology is important, many of our students leave campus to conduct these projects at our international project sites. The project is a degree requirement for all students.*

CDR *Completion of Degree Requirement Form. The form is signed by the faculty advisor when the final project report is completed and graded. It is proof that the student has satisfied the degree requirement and is filed with the Registrar.*

PRC *Program Review Committee. This is the department undergraduate committee that annually reviews all senior transcripts to ensure all degree requirements are met for graduation.*

So, let us go through the matrix using "an ability to function on multidisciplinary teams" for our first example. The performance criteria is that students complete a team-based IQP, and the practice is that we require all students to do these projects. Project assessment is done by the faculty advisor and is documented by a grade appearing on the CDR form. This is accomplished for nearly all students by the end of the junior year. The feedback process involves the PRC—if a student does not complete the project, then the PRC issues paperwork informing the student and the Registrar of that fact. Superficially, this might look okay. These projects are truly multidisciplinary (you will have to take my word for that), so completing one with a passing grade, or being duly informed if you did not, may seem like a reasonable assessment loop. Until recently it appeared to be so, but a critical reexamination of the matrix makes me now think otherwise.

I believe that a real assessment plan must go deeper. Completing such a project is not always a guarantee that students function effectively in teams since a dysfunctional team could still pass this degree requirement. Unless an evaluation of effective teamwork is a documented part of the advisor's grading policy, we cannot be sure about the students' abilities relative to the objective. If we believe that argument, then the grade alone is not the proper assessment method. A tool that measures teamwork effectiveness must replace it, and measurable standards of effective teaming must be defined. It logically follows that the PRC review is not adequate feedback. If our teamwork-effectiveness tool indicates that significant numbers of students do not meet our standards, then somehow we must find a way to include team-building activities into the process and formally document the procedure. Some faculty may claim that such a move threatens their academic freedom as project advisors. This issue may arise any time faculty are asked to include new course activities for outcomes assessment purposes. We, and other universities, must deal with this issue as assessment plans are developed.

Here is another example (objective "h"): "...the broad education necessary to understand the impact of engineering solutions in a global/societal context." Compare this objective to the goals of the IQP and you will see they are quite

TABLE 1
Portion of the Department Assessment Matrix

Objective	*Performance Criteria*	*Practices*	*Assessment Method*	*Frequency*	*Feedback Process*
d) an ability to function on multidisciplinary teams	-complete a multistudent IQP	-IQP opportunities are available for every student	-CDR form	-Jr. year	-PRC audit, academic advisor
h) the broad education necessary to understand the impact of engineering solutions in a global/societal context	Demonstrate an understanding or interest in the global or societal implications of engineering by: -completing an IQP abroad	WPI has extensive overseas IQP	-CDR forms	-Jr. year for IQP	-WPI IQP review

similar. What better way to satisfy this objective than to complete one of these projects outside the United States? Such an experience includes a multidisciplinary team working in a government agency, a company, or a non-profit organization in another country on a topic interfacing technology and society. Our assessment plan for this item has some of the same problems described above, but we focus here on a different aspect.

WPI has an outstanding and extensive global-projects program. We send more engineering students overseas for such projects than any other university in the country[8]—quite surprising considering our relatively small enrollment. But last year, only one-third of our students went off campus for their IQP experience. This means that two-thirds of our students did not satisfy objective (h) unless they completed some other appropriate, but as yet unknown, academic experience. Should we try to send all our students outside the U.S., or do we modify the on-campus curriculum to provide alternate paths? Both are viable options, but neither is simple. What about other schools? Should a large university initiate such an extensive global-projects program? The expertise, resources, and organization needed to run such a program are not trivial. Can this objective be equivalently addressed in a course about global engineering? Does that dilute the academic impact so much that the original intent of this objective is lost? We are currently exploring possible answers to these questions. The process is part of what EC 2000 is all about.

Clearly and efficiently linking measurable outcomes to objectives is key to preventing instability in the assessment process. Good objectives with poor evaluation tools means we have little idea if educational goals are met. Good objectives and tools with no feedback means no improvement will occur. Vague objectives, poor evaluation strategies, and excessive assessment will choke the life out of an academic system—an instability we must avoid. Chemical engineers have the skills to design and control complicated chemical processes. Although some adapting is required, we are in a good position to apply those skills creatively to good assessment design.

SUMMARY

The consequences of EC 2000 will be different for each school. The two examples from WPI's assessment plan described above illustrate two major points:

- *Designing and conducting a rigorous outcomes-based assessment process for engineering education is a complex task.*
- *We will all have to change the way we do business. This includes the way we educate and interact with students, the way learning is measured, and the way we use the data.*

If universities and ABET take this approach seriously, then we must do it right to make it meaningful.[5] It is a challenging problem that is well worth our efforts. This holistic approach to education frees us from the rigidity of past accreditation philosophies. New curriculum flexibility is possible, so long as we document its successes and use its failures for improvement. Yes, our learning curve may be steep, but if we maintain high performance standards, our students will ultimately be the main beneficiaries of these efforts.

An answer to our earlier question about why we should assess included something about putting meaning into our instruction and knowing that students learn what we want them to learn. Typically, we focus only on the technical content. The new accreditation criteria add a human element into the process. Perhaps this element coupled with good assessment plans will ensure that students go beyond our earlier answers and learn "how to learn." This certainly gets at the heart of what teaching is all about and may help guarantee that our students become lifelong learners.

NOTE: ACKNOWLEDGMENTS

The opinions expressed in this paper are solely those of the author and do not necessarily represent those of Worcester Polytechnic Institute, the Chemical Engineering Department of WPI, or the Accreditation Board for Engineering and Technology. The author gratefully acknowledges Natalie A. Mello (Interdisciplinary and Global Studies Division, WPI) for reviewing the manuscript and suggesting several improvements.

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Engineering Flow and Heat Exchange

Revised Edition
by *Octave Levenspiel*
Plenum Press, New York and London (1998)

Reviewed by
Gabriel I. Tardos
CCNY

This is the first revised edition of this book, first published in 1984. Professor Levenspiel should be commended for producing such an excellent text, written specifically for engineering students. The book is a pleasure to read and offers several amusing problems, all stated in the language of students, with explanations and examples they can easily understand. Very few texts in engineering can make such a claim. I have used this text exclusively since 1992 in my teaching of unit operations to chemical engineering students. The material is broad enough, however, to also be used in mechanical engineering, and perhaps in civil engineering courses as well, to teach flow and heat transfer.

Students (especially undergraduates) tend to sell used textbooks once they finish a subject and pass their final examination. I found, with great pleasure, that *Engineering Flow and Heat Exchange* was not one of those books; seniors use it in their design courses and many graduates keep the book as a reference. This is obviously due to the wealth of information in the book and the ease with which the information can be retrieved and used. Inclusion of compressible and non-Newtonian fluid flow in the fluid-mechanics section and direct-contact heat exchangers in the heat-exchangers section is a substantial achievement and significantly adds to the usefulness of the text.

One example of the book's unique approach to explaining a complex concept through humor and straightforward, easy-to-understand language is illustrated by how Professor Levenspiel explains the concept of equivalent average slurry density in the problem "Counting Canaries Italian Style." The "slurry" consists of canaries flying in the air inside a closed container. Measuring the pressure before and after the canaries are airborne, and using the Bernoulli equation, gives the change in density and therefore the number of "particles" (birds). Ingenious!

As already mentioned, the book is divided into a section on fluid mechanics and a section on heat transfer. The first part includes basic equations for isothermal flowing systems in Chapter 1, and as an example, flow of incompressible Newtonian fluids in pipes and around solid immersed objects in Chapters 2 and 8, respectively. Unlike other similar texts, the theory is kept short and the assumption is that the student has taken a prior course in fluid mechanics. It is assumed, for example, that the student is familiar with the concept of the Fanning friction factor.

Chapters 3 and 4 address compressible flow of gases (through material taken mostly from thermodynamics) and low pressure, "molecular" flows. The concept of "molecular slip" is introduced here.

Chapter 5 contains, as mentioned above, concepts and problems of non-Newtonian flow explained in a direct and simple-to-understand fashion. The student is reminded that, in general, this complex fluid can be treated as Newtonian with an additional term and all that is required is to find the correction due to the non-Newtonian behavior. Since most fluids in industrial practice are non-Newtonian, the introduction of this material is, I think, crucial. Furthermore, rheometry to measure non-Newtonian behavior is also presented in detail.

Part one of the book, also contains chapters of flow in porous media and in fluidized beds. They are also well written, with many examples and actual industrial applications both solved and presented as homework problems.

The second part of the book, on heat transfer and heat exchanger design, is also enlightening, crisp, and well constructed. Chapters 9, 10, 12, and 13 contain the usual material on different forms of heat transfer, combined heat transfer, and two-fluid heat exchanger design. Here again, it is assumed that the student has taken a previous introductory course in heat transfer since familiarity with, for example, the Nuselt number is required. The material in Chapters 11, 14, and 15 contains unsteady heating and cooling and design of direct-contact exchangers and regenerators—material usually not covered in standard texts. The second part ends (Chapter 16) with a set of recommended problems involving material contained in the book, keeping in mind practical, industrially relevant applications.

There is an extended Appendix with very useful information such as transformation of units, some material properties, dimensionless groups, and values of more important parameters such as heat transfer coefficients in different geometries. The text also comes with a set of solutions (available to the instructor) to the problems in each chapter, with every second problem being solved. The problems in the last chapter (16) all have solutions. The illustrations in the book are inspired and clear, while the nomograms, mostly for heat transfer calculations, are up-to-date and easy to use.

Over all, this is an excellent book, written with the heart. The reader can visibly appreciate this. It should be a permanent fixture on the bookshelf of any engineer who studied or uses fluid flow and heat transfer in his work. ❐

THE ARTICULATION MATRIX

A Tool for Defining and Assessing a Course

BARRY MCNEILL, LYNN BELLAMY
Arizona State University • Tempe, AZ 85287-6006

As ever-increasing numbers of students initially attend community colleges, articulation is a concern of public universities. Articulation issues are particularly difficult for engineering design classes, which tend to be institutionally dependent. In Arizona, a task force of university and community college engineering faculty addressed this issue for the first-year engineering design class, and a process, based on the educational research work of Tyler[1] and Bloom,[2] was developed. It involved creating and analyzing an Articulation Matrix—a matrix that shows the educational relationship between a course's learning activities and learning objectives. One strength of the developed process was the creation of an explicit assessment process to determine if a proposed course was acceptable.

CREATING THE ARTICULATION MATRIX

In Arizona, the first-year engineering (design) course is a cornerstone in each of the three state university's BS engineering curriculum. Since introductory design courses do not generally have the type of defined learning objectives found in a statics or dynamics course, these introductory courses tend to be unique at each of the three universities. With the large number of students who want to take the first-year engineering course at a community college, the three unique courses have made it very difficult for the community colleges to offer a course that could transfer to all three universities. The community colleges have been forced to select the university most of their students are likely to attend and then develop a course consistent with it. Articulation problems extend beyond community colleges to include all course transfers between schools of engineering.

In the fall of 1996, a task force* of faculty from the three universities and several community colleges started work on this articulation problem. They were faced with the standard articulation issues of

- *What topics, skills, etc., to include in the first-year design course*
- *How to ensure (establish) that a proposed course was, in fact, satisfactory*

and, a third issue to be considered

- *How to address the first two issues in a manner such that a school still had the flexibility to develop its own unique character for the course, using the school's interests and strengths.*

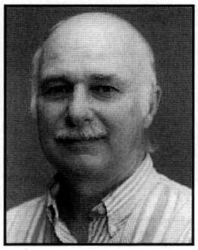
The task force developed a process that satisfactorily addressed all three of the issues. The process requires the creation and use of an Articulation Matrix, so called because it helps resolve the articulation problem.

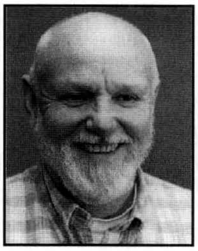
This paper will first present the educational theory upon which the Articulation Matrix is based, followed by a general discussion of the Articulation Matrix and how to create and analyze it. It will conclude with two examples, one showing how the matrix was used in the articulation process and one showing how the matrix could be used as part of an ABET EC 2000 accreditation effort.

THE EDUCATIONAL THEORY

The educational basis for the Articulation Matrix comes from the published work of two School of Education faculty members at the University of Chicago, Ralph Tyler[1] and Benjamin Bloom.[2] Tyler formulated a basis for defining a course or curriculum, while Bloom worked to clarify the

Barry McNeill *received his BS in chemical engineering from Stanford University in 1962 and his MS and PhD in mechanical engineering from Stanford in 1976. His current interests include the design process, how to teach design, and assessment.*





Lynn Bellamy *obtained a BS in chemical engineering from Texas A&M University in 1962, and MS and PhD degrees in Engineering Science from Tulane University in 1965. His interests are in asynchronous and distance learning.*

** Vern Johnson (U. Arizona), Spencer Brinkerhoff and Pamela Eibeck (Northern Arizona U.), Dan Jankowski, Lynn Bellamy, and Barry McNeill (Arizona State U.), Mel Heaps (Cent. Arizona College), Dave May (Pima Com. College), and Don Yee (Mesa Com. College).*

terms used in describing how well a subject has been mastered.

Defining a Curriculum (Course) • Criterion 2 of ABET EC 2000[3] requires a school to have and use a defined process for the development and continuous improvement of its curriculum. How to satisfy Criterion 2 has created a rash of interest and a plethora of papers and workshops. But the issues involved in Criterion 2 are not new and were addressed in the late 40s by Tyler. In 1949, he published a short treatise on the basic principles involved in curriculum and instructional development. His work is neither a textbook nor a manual on curriculum development, but rather the "rationale for viewing, analyzing, and interpreting the curriculum."

Tyler's approach involves answering four basic questions:

1. *What educational purposes should the school seek to attain?*
2. *What educational experiences can be provided that are likely to attain these purposes?*
3. *How can these educational experiences be effectively organized?*
4. *How can we determine whether these purposes are being attained?*

Criterion 2 requires schools to: define a set of learning objectives (*i.e.,* answers to question 1); define a strategy to accomplish the learning objectives (*i.e.,* answers to questions 2 and 3); and define an assessment process to measure achievement of the learning objectives (*i.e.,* answers to question 4).

Learning Objectives—Two-Dimensional Vectors • The first step in defining a course or curriculum is development of a set of learning objectives, sometimes called learning outcomes. At first glance, the exemplar learning objectives published in the literature appear to be one-dimensional, *i.e.,* only a subject, topic, or skill to be learned.[4,5] But upon closer observation, the objectives also define some level of performance associated with the competency (*e.g.,* "graduates will be able to identify, formulate, and solve..."[4] or "will exhibit good listening skills"[5]).

Learning objectives are two-dimensional vectors consisting of a competency and a degree to which the competency is learned or mastered. Of these two parts, the first is the easiest to define precisely. The competency is the subject, topic, or skill to be learned (*e.g.,* integration by parts). Precisely defining the degree to which a competency is mastered is more difficult. For example, what does "really understands integration by parts" mean? While this example could be improved and made more specific, the effort is probably not worthwhile, especially if every competency needs its own special wording. Rather, what is needed is a concise, precise, agreed-upon set of terms that can be used to define the degree to which any competency is mastered.

In the mid-50s, Benjamin Bloom, David Krathwohl, and others addressed this problem and developed two taxonomies of educational objectives, one for the Affective Domain[7] and one for the Cognitive Domain.[2] In the foreword to the Cognitive Domain book, Bloom states that the book was "especially intended to help them [those involved in the development of curriculum and courses] discuss these problems [defining how much is learned] with greater precision," which is exactly what is needed. (While this paper only addresses the cognitive domain, understanding the affective domain is a precursor to appreciation of the cognitive issues.)

The cognitive taxonomy was developed assuming that

- *There are different degrees of learning to which someone can know and use information*
- *The different degrees of learning are observable and measurable*
- *The degrees of learning are reasonably hierarchical*

The first and second assumptions reflect the observation that there are noticeable, measurable differences between a novice and an expert in how they use information. The third assumption is based on the observation that successful demonstrations of the higher degrees of learning are generally not possible before successful demonstrations of mastery of the lower levels.

In the early 1990s, David Langford[8] updated Bloom's taxonomy, renaming the learning objectives to Levels of Learning (LoL). The six Levels of Learning, from lowest to highest, are: *Knowledge* (K), *Comprehension* (C), *Application* (Ap), *Analysis* (An), *Synthesis* (S), and *Evaluation* (E).

Bellamy and McNeill[9,10] modified Langford's definitions to reflect the type of activities found in engineering education. An example of how the *Knowledge* Level of Learning is described can be seen in Table 1 (following page). The description includes information from both the student's and the teacher's point of view. The list of *process verbs* at the end of the description is very helpful in distinguishing between the various levels of learning.

OVERVIEW OF THE ARTICULATION MATRIX

The Articulation Matrix is a concise way of presenting the answers to Tyler's first two questions. Further, it presents the data in a manner that makes it possible to also partially answer Tyler's third and fourth questions. The matrix consists of a set of rows (the learning objectives), a set of columns (the class activities) and a set of letters indicating the LoL impact, if any, each activity has on each learning objective (see Figure 1, which will be discussed later). Tyler included an early version of the matrix on page 50 of his book. To better understand the matrix, consider how it is used to help answer each of Tyler's four questions.

Question 1: Defining the Learning Objectives • Answering the first of Tyler's questions requires stating the course's learning objectives (competencies and associated changes in LoL). The processes used to generate the learning objectives are many and varied (*e.g.,* 4, 5, and 6) and will not be discussed here. Once the learning objectives have been developed, they can be entered into the Articulation Matrix. First, the competencies are entered. Since there is often a hierarchy associated with the competencies, the matrix allows for this by having *Competency Categories* as well as *Competencies* under each of the categories. Thus, in Figure 1, there are two major competency categories (Engineering Design Process and Working in Teams) and eight competencies (*e.g.*, formulating the problem, team communication) shown.

Next, to complete the entry of learning objectives, the change in LoL for the *Competency Categories* and *Competencies* must be entered. The change in LoL is indicated by showing the required input level and the desired output level in the second and third matarix columns. Thus, in the matrix shown in Figure 1, the change in LoL for "solving a problem" (competency 1.2) is from *Unaware* (a "U" in the second column) to *Application* (an "A" in the third column).

Question 2: Defining Course Activities and Their Impact • Once the learning objectives have been entered, it is possible to answer Tyler's second question. This is generally an iterative process with the completed matrix showing the results of the final iteration. The general process involves adding all the class activities, one at a time, to the matrix, indicating in the body of the matrix which learning objectives are impacted by the activity, and finally indicating the degree of learning possible using the activity.

Consider the fourth activity, "orally report to peers and class," shown in Figure 1. When this activity was entered into the matrix, it was felt that it impacted all the shown competencies except for competency 1.5. Further, the impacts were all judged to be at the *Comprehension* LoL; that is, the "C" in the "solving a problem" competency row indicates that when the activity is completed, the students could have demonstrated mastery of "solving a problem" at the *Comprehension* LoL. This example matrix is rather dense, *i.e.,* many of the activities impact on many of the learning objectives. It is not uncommon to have less dense matrices.

There is an alternative, somewhat easier but less educationally rigorous, method for completing the matrix. In this alternative method, the competencies are loosely viewed as the *needs* and the activities as the *hows* in a House of Quality.[11] Thus, in filling out the matrix, instead of indicating the LoL, a symbol indicating the degree of impact (high, medium, low) that the activity has on the competency is entered into the matrix. This method does give a good picture of which activities have the biggest impact on the learning, but a matrix completed using this method is much harder to use when attempting to address Tyler's last two questions.

Question 3: Organizing the Course Activities • Since the previous step focused only on entering all the course activities into the matrix, the columns in the matrix are generally not in the desired order, *i.e.,* the actual sequence followed in the course. This can be seen in Figure 1 where there are "Out-of-Class Activities," shown late in the matrix, that would actually occur early in the course (*e.g.,* "read and summarize textbooks"). While the matrix may not have the activities organized, it does contain information that can be

TABLE 1
Activities of Students and Teachers at the Knowledge Level of Learning[10]

Knowledge (Information) Level of Learning

- How do **I know** I have reached this level?

  I can recall information about the subject, topic, competency, or competency area; I can recall the appropriate material at the appropriate time. I have been exposed to and have received the information about the subject; thus, I can respond to questions, perform relevant tasks, etc.

- What do **I do** at this level?

  I read material, listen to lectures, watch videos, take notes; I pass "true/false," "yes/no," "multiple choice," or "fill in the blank" tests that demonstrate my general knowledge of the subject. I learn the vocabulary or terminology as well as the conventions or rules associated with the subject.

- How will the **teacher know** I am at this level?

  The teacher will provide verbal or written tests on the subject that can be answered by simply recalling the material I have learned about this subject.

- What does the **teacher do** at this level?

  The teacher directs, tells, shows, identifies, examines the subject or competency area at this level.

- What are typical ways **I** can demonstrate my knowledge?

  1. *Answer "true/false," "yes/no," "fill in the blank," or "multiple choice" questions correctly.*
  2. *Define technical terms associated with the subject by stating their attributes, properties, or relations.*
  3. *Recall the major facts about the subject.*
  4. *Name the classes, set, divisions, or arrangements that are fundamental to the subject.*
  5. *List the criteria used to evaluate facts, data, principles, or ideas associated with the subject.*
  6. *List the relevant principles and generalizations associated with the subject.*
  7. *List the characteristic methods of approaching and presenting ideas associated with the subject (e.g., list the conventions or rules associated with the subject).*
  8. *Describe the general problem-solving method (i.e., the techniques and procedures) or the method(s) of inquiry commonly used in the subject area.*

- What are typical **work products**?

  1. *Answers to Knowledge-level quizzes ("true/false," "yes/no," "fill in the blank," or "multiple choice").*
  2. *Lists of definitions or relevant principles and generalizations associated with the subject.*
  3. *Modifications of example problems presented in the textbook; for example, modest changes in numerical values or units; i.e., solutions to problems that were solved using "pattern recognition."*

- What are descriptive **"process" verbs**?

define	label	listen	list	memorize	name
read	recall	record	relate	repeat	view

used to help establish some of the desired organization.

Tyler suggests that the two major course organizational considerations are 1) how to organize for the continual growth in LoL for a competency, and 2) how to organize for cross-competency requirements (*i.e.,* pre- and/or co-requisite competencies). The Articulation Matrix can help with the first, but not the second, of these considerations. Assuming Bloom's taxonomy is hierarchical, the activities for a competency need to be scheduled to begin with the lowest LoL and proceed sequentially to the highest LoL. Thus, the matrix shown in Figure 1 suggests that for the "formulating the problem" competency, the *Knowledge* activities should occur early, the *Application* activities should occur late, and the *Comprehension* activities should occur in between.

Question 4: Assessing the Course • Tyler's fourth question concerns assessment. While the Articulation Matrix is not directly concerned with student assessment, it can help in two assessment areas. First, the matrix can be used to pre-assess the course to determine if it has the potential of delivering the desired objectives. Second, the matrix can help select assessment instruments for the various course activities.

Pre-Assessment of the Course. After all the course activities have been entered and their impact entered in the matrix, the matrix can be evaluated to confirm that the proposed course is complete and has the potential to allow students to achieve the predefined learning objectives. In pre-assessing the course, there are four considerations:

1. *Is there at least one course activity that impacts each of the competencies (i.e., no empty rows)? If there are empty rows, one or more course activities must be added to the matrix or an existing activity must be modified so it impacts the competency.*
2. *Is there at least one competency impacted by each course activity (i.e., no empty columns)? If there are empty columns, the course activity does not impact any of the course learning objectives and should be eliminated.*
3. *Does each row have an adequate number of appropriate course activities? If the competency has an expected multilevel change in LoL (e.g., from* Knowledge *to* Analysis*), are there activities at the intermediate LoL's (e.g.,* Comprehension *and* Application*) as well as the final expected level (e.g.,* Analysis*)? Are there too many or too few activities at any given level? Any "No's" must be addressed by adding or removing activities, modifying other activities so they impact the problem competency, or changing the LoL associated with the competency to match what is actually possible.*
4. *Do at least 75% of the competencies for a competency category have course activities at the LoL stipulated for the competency category? If the answer is "no," then either more activities at higher LoL must be added or the competency category LoL must be reduced to match the LoL of the activities shown in the matrix.*

Competencies	Level of Learning (in)	Level of Learning (out)	Course Activities	In Class Activities	take quizzes/exams before class	active learning exercises	construct mathematical models	orally report to peers and class	peer assess design notebooks	work on design projects	watch manufacturing/other videos	listen to brief lectures	Out of Class Activities	read and summarize textbooks	construct model based on geometry	Projects	dissect and reassemble artifact	develop an assembly plan (process)	design, build, and test a device	demonstrate design
1. Engineering Design Process	U	A																		
1.1 formulating the problem	U	A			K	C		C		C		K		K			C	C	A	A
1.2 solving a problem	U	A			K	C		C		C		K		K			C	C	A	A
1.3 implementing a solution	U	A			K	C		C		C		K		K			C	C	A	A
1.4 documenting the process	U	A			K	C		C		C		K		K			C	C	A	A
1.5 using engineering/physical principles	U	K					K													
1.6 using quality principles	U	A			K	C		C		C		K		K			C	C	A	A
2 Working in Teams	U	C																		
2.1 team dynamics	U	C			K	C				C		K		K			C			
2.2 team communication	U	C			K	C				C		K		K			C			

Level of Learning Legend U Unaware K Knowledge C Comprehension A Application

Figure 1. *A portion of ASU's first-year design course Articulation Matrix.*

The first two are easy checks and help ensure that all the course learning objectives are addressed in one or more of the activities and that there are no extraneous activities (*i.e.,* activities that have no impact on the desired learning objectives). The answers to the third and fourth questions are a bit more subjective. The third assessment question focuses on each competency, to ensure that there are enough activities at the appropriate LoL's so a student could reasonably be expected to achieve the desired LoL by the end of the course. The fourth question focuses on whether there are enough course activities at a high enough LoL to ensure that the entire competency category LoL is achieved. The use of 75% is somewhat arbitrary and may be modified with experience.

Assessing the matrix shown in Figure 1 leads to the following conclusions. First, each row has at least one activity that impacts on the competency. Second, there are two activities ("peer assess design notebooks," "watch manufacturing videos") that appear to impact no learning objectives and should be considered for removal (they actually impact several competencies not shown in this partial view). Third, the mix of activities for each competency is good. For example, there are three *Knowledge*, five *Comprehension*, and two *Application* activities for the first set of competencies. It is possible that there are actually too many *Comprehension* activities. Finally, the competency LoL's support their competency category LoL's. For example, five of the six competencies (83%) under the "Engineering Design Process" competency category have activities at Application LoL, which is the desired LoL for the competency category. It would appear that this course is acceptable and should articulate.

Assessment Instruments. Once the expected LoL is known for an activity, the method of assessing whether the students have achieved the LoL needs to be determined. As with the learning objectives, the requirements of EC 2000 have spawned many articles and workshops on assessment. Since the LoL of the activity has been defined, there are several places to find appropriate assessment instruments. First, the work by Angelo and Cross[12] on classroom assessment can be reviewed. Next, Bloom[2] can be reviewed; it contains a number of typical testing methods that can be used for each LoL. Third, the definitions of the various LoL's[9,10] provide a variety of different ways of looking at each LoL, allowing the generation of appropriate assessment instruments. For example, material for *Comprehension* LoL[9,10] states that students should be able to explain (orally or written) their solution process. This suggests that for *Comprehension* LoL activities, a discussion of the process should be required.

USING THE ARTICULATION MATRIX

While the Articulation Matrix was developed to resolve the first-year engineering design course articulation problem, it has become clear that it has a wider application. Two applications will be discussed: one that uses the matrix in course articulation and one that uses it as part of the EC 2000 accreditation process.

Course Articulation Within a State • The starting point for this work was the fact that design courses did not articulate at the three state universities. The task force developed a two-step process to resolve this problem. In the first step, the task force defined the desired learning objectives (six competency categories and twenty-two competencies) and entered them into a blank matrix, creating a "skeleton" Assessment Matrix (Figure 1 shows part of this matrix; see Reference 13 for the complete skeleton matrix). Much of the task force's work involved explicitly defining the learning objectives and developing a complete glossary of operational definitions[13] ("operational definition" is the agreed-upon meaning of the term) for each *Competency Category* and *Competency* in the matrix. Finally, the task force added several topic and activity constraints to ensure the course included the desired type of experience (*e.g.,* at least two extensive, 3-to-6-week projects). Once the skeleton matrix was completed, the task force was done; the various schools then completed the matrix during step two of the process.

In the second step of the articulation process, each school (university, community college) that wanted to offer a course that would articulate started with the skeleton matrix and constraints and then completed and assessed an Articulation Matrix for their proposed course. The task force developed an assessment checklist to aid in the assessment step. Any course that passed the assessment step would articulate at all of the three state universities.

The strengths of this process are twofold. First, having each school start with the skeleton matrix allows considerable flexibility in defining how the learning objectives are met. Each school can use activities that suit its nature and strengths. The only constraint is to have enough activities at the appropriate LoL. Second, having a defined assessment step takes the uncertainty out of the articulation process. A community college need no longer wonder if its course is satisfactory. Any questions that do arise (*e.g.,* Does that activity actually allow *Comprehension* LoL?) can be easily resolved by supplying samples of student work for the activity in question.

EC 2000 Accreditation Process • While experience to date has been primarily limited to using the matrix to resolve articulation problems, the process of developing the matrix is general and can be easily extended to defining a curriculum (*e.g.,* the Mechanical and Aerospace Engineering Department at Arizona State University has developed the curriculum matrix for its two undergraduate degrees). When using the matrix for a curriculum, the following changes are made:

1. *The learning objectives, i.e., the rows, are the objectives related to the entire curriculum and not just a course.*
2. *The columns become the courses in the curriculum instead of class activities.*
3. *The LoL impact indicates the maximum LoL expected to be achieved in the course.*

Part of the matrix for a chemical engineering curriculum is shown in Figure 2. Looking at the rows, the curriculum shown in the figure shows that the students are expected to enter the curriculum at *Unaware* and to leave at *Synthesis* LoL for "Modeling." How this transformation is accomplished is partially shown by looking at the two modeling sub-competencies. The students are expected to achieve *Knowledge* LoL about "conservation and accounting" in their first-year chemistry courses and *Analysis* LoL in ECE 201.

Competencies	Level of Learning (in)	Level of Learning (out)	English 101 and 102	General Studies	Economics 111 or 112	Chemistry 113	Chemistry 116	Chemistry 331 (organic)	Chemistry 332 (organic)	Chemistry 335 (organic lab)	Mathematics 270 (differential calculus)	Mathematics 271 (integral calculus)	Mathematics 272 (series)	Mathematics 274 (ODE)	ECE 100 (introduction to design)	ECE 300 (intermediate design)	ECE 201 (conservation principles)	ECE 202 (properties of mater)
1. Fund. Math & Science	K	Ap																
1.1 calculus	U	Ap									C	C	C	C			Ap	Ap
1.2 general chemistry	K	Ap				C	C									Ap		
1.3 organic chemistry	K	Ap						C	C	Ap								
2. Modeling	U	S																
2.1 principles of modeling	U	S													C	Ap	Ap	Ap
2.2 conservation & accounting	U	S				K	K										An	

Level of Learning Legend

U Unaware	K Knowledge	C Comprehension	Ap Application
An Analysis	S Synthesis	E Evaluation	

Figure 2. *Part of an Articulation Matrix for a chemical engineering curriculum.*

The "principles of modeling" are developed to the *Comprehension* LoL in the first-year design class and are then demonstrated at the *Application* LoL in the upper-division classes.

Looking at the columns of the matrix is also instructive. Figure 2 shows that the conservation principles course (ECE 201) is expected to offer the students a chance to demonstrate *Application* LoL for "calculus" and "principles of modeling," and *Analysis* LoL for "conservation and accounting" modeling. How the course might achieve these LoL goals is not shown in the matrix; this information would be shown on the course matrix.

As with the course matrix, the curriculum matrix can be used to sequence courses. The matrix in Figure 2 shows there are six courses that have an impact on the calculus competency. Based on the LoL shown in the matrix, it appears that Mathematics 270, 271, 272, and 274 should come before ECE 201 (*i.e., Comprehension* before *Application*). The "calculus" row in the matrix highlights the expectation that students are **not** entering ECE 201 with the ability to recognize when to use the calculus skills they have learned (*Application* LoL); rather, *Application* LoL for "calculus" will be achieved in ECE 201 and other upper-division courses.

Finally, the potential success of the curriculum can be assessed much as a course is assessed. For the curriculum, the third assessment question concerns whether there are, realistically, enough courses to move the students through the desired change in LoL. It is reasonable, at the lower LoL's, to expect to be able to move a student through three (and possibly four) levels in one course. But for the higher LoL's, it is difficult to move through more than one or two levels per course. It is not reasonable to expect to take a student from *Unaware* through *Synthesis* or *Evaluation* LoL in a single course. The matrix in Figure 2 is clearly not complete; there are no courses shown at the *Synthesis* LoL for any of the "modeling" competencies.

The use of a matrix to define a curriculum is not new. Olds and Miller[4] defined just such a matrix. The mapping between our matrix and that of Olds and Miller is simple. Their "Program Objectives" become the *Curriculum Competencies*, the "Implementation Strategies" become the courses in the curriculum, and the "Performance Criteria" and "Assessment Methods" become the LoL designations. An advantage of the articulation matrix is that it facilitates assessment of the curriculum.

One final note: it should be possible, using a set of Articulation Matrices, to create a highly compact integrated picture of a curriculum. The first Articulation Matrix in the package would be the curriculum matrix. Then, using the curriculum matrix's *Competency Categories* and *Competencies* as the skeleton matrix, the Articulation Matrices for each course in the curriculum would be created. The desired LoL changes for the course Competencies would come from the LoL changes shown in the body of the curriculum matrix. For example, if the curriculum matrix is that shown in Figure 2, then the course matrix for ECE 201 would show "An" (*Analysis*) for the LoL (out) column and "K" (*Knowledge*) for the LoL (in) column for "conservation & accounting" competency. This package of matrices documents the integrated nature of a curriculum, something required by ABET EC 2000.

SUMMARY

A process that allows Arizona's universities and community colleges to independently develop a first-year engineering design course that will articulate at all of the state's three universities was the focus of this paper. The process uses an Articulation Matrix that shows the educational relationship (Level of Learning achieved) between a course's learning activities and its learning objectives. The matrix was developed using the educational research of Tyler and Bloom. A strong point of the process was development of the assessment method used to determine if a course is acceptable (*i.e.,* allows the students to achieve the course learning objectives). The matrix can be used for any course and is a good way to evaluate a course syllabus. A similar matrix can be used to show how curriculum competencies can be defined, an EC 2000 task.

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BUILDING THE EC 2000 ENVIRONMENT

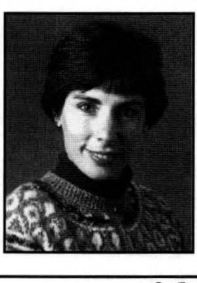
Daina Briedis
Michigan State University • East Lansing, MI 48824

By now, most engineering faculty have accepted the fact that accreditation of engineering programs according to ABET EC 2000 is inevitable. No further introduction or justification of the new criteria is required; it is simply time to "just do it."

Over the past several years, EC 2000 has been the topic of discussion at ASEE and FIE conferences, at assessment workshops, and among engineering faculty nationwide. It has been quite common to hear comments similar to those we hear from students who are reluctant to begin a tough assignment: "When is this due?" "Will this material be on the final?" "What do I do to get a 'C'?" As Dr. Gloria Rogers, Dean for Institutional Research and Assessment at Rose-Hulman Institute of Technology, stated at the 1998 Annual ASEE conference,[1] the hope is for engineering programs to get more than a "C" as we proceed into implementation of successful assessment and improvement processes. But as George Peterson, Executive Director of ABET, confirms, no one expects this to be easy.[2]

THE TIDE IS TURNING

There has been a noticeable turning of the tide. Among these same reluctant faculty, there can be seen, at a minimum, resignation to the fact that accreditation according to EC 2000 will happen. Even more commonly observed is an approach to assessment and program improvement as a scholarly activity that will yield positive outcomes; engineering faculty across the country are rolling up their collective sleeves to begin the task set before them.



***Daina Briedis** is Associate Professor in the Department of Chemical Engineering at Michigan State University. She received her PhD in chemical engineering at Iowa State University and her BS in engineering science at the University of Wisconsin-Milwaukee. She has served as a chemical engineering program evaluator of ABET for over ten years and is a member of both the Education and Accreditation Committee of AIChE and the Engineering Accreditation Commission of ABET.*

I consider myself fortunate in having been able to serve as a program evaluator on an EC 2000 visit while in the midst of my own department's preparations for an EC 2000 accreditation visit (in the fall of 1998), and thus observing from both sides of the fence. There has been no better EC 2000 "crash course" than these combined experiences.

In writing this paper, I do not represent ABET's Engineering and Accreditation Commission (EAC), since ABET is deliberately not prescriptive about the nature of quality improvement processes adapted by individual programs. The spirit of EC 2000 is, in fact, to encourage programs to establish their own customized objectives and improvement processes that are tailored to that particular institution's and program's mission and are responsive to the needs of their constituencies. Rather than proposing a set of instructions, this article simply relates experiences and lessons learned. Two topics that frequently surface in discussions about EC 2000 are examined: constituency "buy-in" and closing of the improvement loop. How these issues affect evaluation and institutionalization of a program-improvement process will be addressed.

A COMMON CAUSE

Several institutions already have well-established program improvement processes in place. These institutions have been motivated by various factors, including the desire to achieve a vision, improvement of teaching, competition with other institutions, state mandates, industrial linkages, or other factors.[3,4] In most of these institutions, assessment and program improvement are the *modus operandi*. For most of the rest of us, this goal is yet to be achieved.

This is not to say that prior to EC 2000 engineering institutions have been operating in an improvement vacuum; for many years, program improvement has been integral to course evaluations, curricular revisions, training and mentoring new faculty, and interactions with employers and industrial advisors. But we have been anecdotal about these methods. ABET criteria now ask us to become more structured, more focused, and much more quantitative regarding program improvement. Furthermore, we are directed to improve in the direction of measurable goals—our program educational objectives—and our student (graduate) outcomes must demonstrate how well we are doing in this endeavor. This additional formalism and documentation is what most faculty find intrusive, in that such up-front planning, careful documentation, measurement against performance standards, and analysis of improvement trajectories all take time and represent a departure from old habits.

BUY-IN FOR THE LONG HAUL

Time *is* a factor. Preparation for an EC 2000 visit, much less the design and implementation of a sustainable program-improvement process, cannot be done overnight. Moreover, not all faculty and students can be expected to contribute willingly or to be 100% committed to the effort. A foundational principle of EC 2000 is that program improvement must be permanently integrated into how engineering programs conduct business. Therefore, as Covey says, we should plan "with the end in mind"[5] in order to develop a sustainable process that the academic staff, faculty, and students will be comfortable with for the long haul.

One way in which the level of sustained commitment to these processes can be significantly impacted is by involving program constituencies in the early planning and preparations. Leonard, *et al.*,[6] describe two such approaches. Hopes for permanent implementation and constituency "buy-in" appear to be maximized if we draw upon current assessment activities, leverage what has already been done, and involve as broad a constituency support base as possible.

BUILDING THE EC 2000 ENVIRONMENT

Since in most institutions the faculty have ultimate responsibility for evolution of academic programs, development of an improvement process may work best and impel faculty most if the effort *proceeds from* faculty. Rather than a process being dictated from outside or from above, faculty must assume some ownership of the planning and implementation steps. Many institutions have set forth in this mode.

<u>Review the Old; Share the New</u> At Michigan State University (MSU), a college-level ABET task force was established in early 1997 to determine the feasibility of an EC 2000 accreditation visit for the 1998-99 cycle. No one assumed *a priori* that a request would be made to ABET for evaluation under the new criteria (this will no longer be an option for accreditation beginning in 2001-02).

Comprised of a faculty representative from each program (some of whom are ABET evaluators) and selected administrators, the group first endeavored to understand EC 2000 and how improvement processes might support the mission of our institution. The task force was also careful to accept and use common definitions for EC 2000 terminology (see Sando and Rogers[7] and the NSF *User-Friendly Handbook to Project Evaluation*[8]). While the ABET two-loop model is useful in understanding steps in the processes for setting objectives and for assessing outcomes, the task force worked with a more traditional feedback model to visualize how EC 2000 fit into academic programs.[9] The model provided reference points on which to peg the focus of our discussions and the results of our efforts.

The task force next began a thorough analysis of the assessment status quo in the college. We inventoried the existing assessment practices, both at the college level and within programs. A complete review of the program self-studies (Volume II) from the previous ABET visit was conducted in order to identify items that overlapped with material being requested for the new criteria. (Since then, Sarin has published an inventory of this type of information.[10]) Because of our lack of expertise in assessment, we sometimes called on industrial and academic experts in this field for advice. In addition, several task-force members attended meetings and workshops to learn as much as possible about best practices in assessment and program improvement. Current literature on these topics was reviewed regularly. Most importantly, information was freely shared among programs, and reports of task-force progress were regularly transmitted to the departmental faculty. Requests for input from departmental faculty were equally frequent. Thus, while faculty had not yet "bought into" the ideas, they were kept apprised of the process from its inception.

<u>Retrofitting</u> With input and support from the college faculty, in April of 1997, the task force voted to recommend a request for evaluation according to EC 2000. Most of the work from this point forward was carried out in the programs, but the task force maintained its role of facilitation and oversight. The task force continued to edit existing college-level assessment instruments for EC 2000 compatibility by fine-tuning for assessment of the skills and attributes represented in the Criterion 3 outcomes. The individual programs were free to choose whether or not to include these college-level assessments in their own toolbox of methods. We did not suggest the adoption of a single assessment and evaluation model for the entire college (as proposed by Aldridge and Benefield[11]). With full knowledge of what was available at the college level, however, the individual programs could streamline their own assessment efforts.

<u>Self-Evaluation</u> The task force members took advantage of two additional ABET documents relevant to the visit preparations, both found in the Manual of Evaluation Process. We regularly scored our own programs on the "Level of Implementation" (Manual of Evaluation Process, Appen-

dix A[12]), which is completed by the program evaluator to assess the extent to which programs have implemented several aspects of EC 2000. Another calibration exercise was to perform the Program Deficiency Audit (PDA). It is used by the visit team as a "roadmap" to criteria deficiencies and their resolution through the entire accreditation process. In our planning efforts, the PDA helped several programs focus their process development efforts in the areas perceived to be weakest.

Lessons Learned This type of college-level approach clearly demonstrated four important points:

- *Sharing and review of information is a valuable practice. It is not necessary that each program reinvent assessment instruments already proven to be effective. In fact, a somewhat unified approach for the entire college is easier to manage and may present a stronger case for sustainability to the ABET program-evaluation team.*
- *It proved time-efficient to retrofit current, in-house assessment and evaluation practices for EC 2000 compatibility. More important than the savings in time and effort was the fact that these were already part of the existing environment.*
- *It was helpful to view our efforts through the eyes of an ABET evaluator. Using the same documents as those used by program evaluators was useful in focusing our planning and implementation efforts.*
- *Even though buy-in from the entire faculty is desired, it was critical to have one individual in each program serve as champion and coordinator of that program's improvement efforts. In fact, as institutions look beyond EC 2000 visits, it is clear that someone or some group must assume responsibility for maintaining the assessment and evaluation processes. Evaluators will undoubtedly be looking for this confirmation.*

At MSU, development of the EC 2000 environment was accorded enough importance that task-force members were compensated in various ways for their efforts. This typically amounted to a fraction of the academic year's release time, a portion of a summer's salary, payment for student help, or some combination of these. In the EC 2000 pilot visits that have occurred, many programs have had "EC 2000 coordinators" who are individuals other than the program administrator. Preparation for an EC 2000 visit and the institutionalization of continuous program improvement processes are significant responsibilities that, if done well, consume more time than any program administrator is able to provide. But support from the program administrator, the college administration, and ideally, the institutional administration is vital to the long-term success of these efforts. While an ABET evaluator may not worry too much about whether or not the EC 2000 coordinator was adequately compensated, financial support does attest to administrative commitment to this effort.

PROGRAM-LEVEL ACTIVITIES

Task-force efforts paved the way for work that needed to be done at the program level, where curriculum committees frequently assumed responsibility for the bulk of the work. Students also became more intimately involved in the processes by virtue of their membership on these committees and in related assessment-development activities.

Modeling We found the use of a process model (see Figures 1, 2, and 3) to be an effective framework for our planning strategies. The model (Figure 1), first used by the task force, was expanded to include a more detailed representation of the relationships among the assessment instruments, implementation strategies, constituencies, and the academic program (Figures 2 and 3). Current assessment literature addresses the various types and hierarchal levels of assessment.[13,14] The process diagram helped us visualize how various levels of assessment would

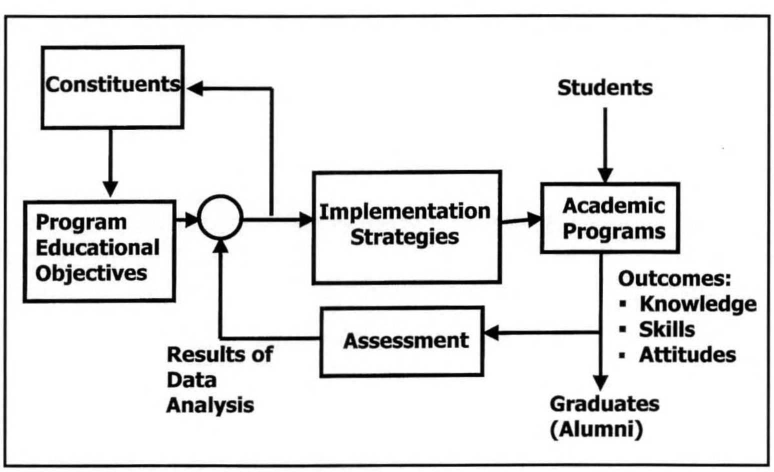


Figure 1. *Program Improvement Process Model.*

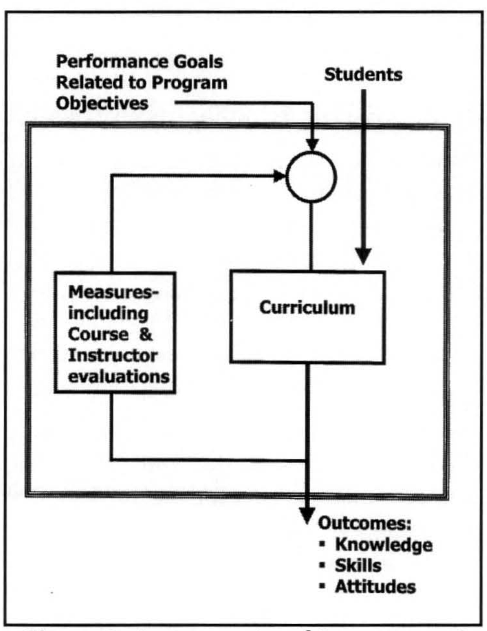


Figure 2. *Assessment and Improvement Process at the curricular level. Detail of the "Academic Programs" block in Figure 1.*

integrate into the overall program improvement process.

Objectives and Outcomes Our department's educational objectives and program outcomes had already been developed through routine departmental and advisory meetings involving faculty, students, industrial advisors, and alumni. Even though we had not cemented a formal process at this point, we had involved the major constituencies of our program and had a starting point in hand. Our focus turned to implementation.

As discussed by Ewell,[3] the major point of contact through which any program achieves its educational objectives is the curriculum, and therefore, we identified how each individual course contributes to achieving our program objectives. A discretized approach was not intended. No one course contributes in achieving all objectives, and some contribute more strongly for some objectives than others. Interestingly, even this preliminary analysis helped us identify program weaknesses where objectives were not supported and outcomes were not realized.

Assessment—Just Do It Early on in our planning, we realized that we could never become assessment experts. Reaching somewhat beyond the "comfort zone" of the faculty, we plunged into "doing" the assessment without having read all of the literature and with the knowledge that the assessment tools we had developed were not "perfect" or even tested. We borrowed some ideas from colleagues and developed strategies of our own. This strategy resembled the typical approach to open-ended design problems—an initial design is completed, the preliminary results are evaluated, and the process is repeated for an improved design.

Our curriculum committee determined that, to assess all program outcomes and to give validating evidence (triangulation) whenever possible, the chemical engineering program would supplement the college-level surveys with several program-level instruments. After initial trials of these surveys, several problems became obvious. First, we had over-assessed. We therefore reduced the scope of some of the surveys and decided to use others less frequently. Second, it took little more than almost useless responses from the first version of a survey to result very quickly in a second, more streamlined and effective instrument. Third, these initial trials quickly established that surveys alone are not enough to demonstrate student outcomes, as required by Criterion 3.

A better testimony of outcomes—the knowledge, skills, and

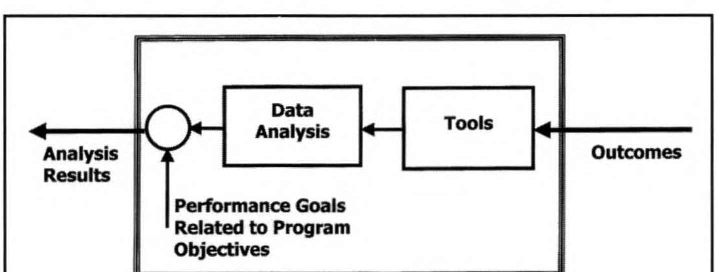


Figure 3. *Assessment and Analysis. Detail of the "Assessment" block in Figure 1.*

attributes acquired by our students—is student work. Our department faculty chose student portfolios as the major means to demonstrate *and* assess course and program outcomes. Initially, a student task force was established to assist in development of the portfolio approach. It established a reasonable set of guidelines for the contents of portfolios, basing its decisions on group discussions and information from the literature.[15] These students gained an understanding of the philosophy of quality improvement and became familiar with ABET EC 2000, thereby becoming a supportive constituency.

Performance Goals An important element of assessment analysis is establishment of performance goals, or performance criteria—specific measures by which to determine if objectives have been met. Programs should have evidence confirming that students and program graduates have achieved the desired level of performance. Performance goals may include such measures as 1) a certain percentage of satisfactory responses on a survey, 2) a target hiring rate for new graduates, 3) specific skills or attributes demonstrated by students, 4) a minimum "score" on student portfolios, or 5) a minimum grade point average. Such performance goals are not only measures of acceptable achievement of objectives, but are also an indication of the relative importance of the objectives to the constituencies—the higher the achievement standard, the higher the implied priority.

Closing the Loop In all of the preparation for the new criteria, it seems that more attention has been paid to assessment rather than what is done with the results of the assessment evaluation. "Closing the loop" is possibly the *key* to EC 2000; many evaluators have found this to be the weakest link in the implementation of program improvement processes. This step can be facilitated if programs use the mechanisms already in place to complete this step.

The academic governance and accountability systems in most engineering colleges are fairly traditional. All academic programs have regular meetings of the entire faculty and of specific subcommittees of the whole. Faculty performance is typically reviewed annually by the head or chairperson. Faculty and staff retreats are common, and advisory board meetings occur periodically. These regular deliberations provide a venue for discussion, review, and action on items related to EC 2000. Using the existing structure enhances the sustainability of the processes and demonstrates to an ABET evaluator that they are "ongoing." If a program has a person or subcommittee responsible for the continued oversight of program-improvement efforts, it is not an onerous task to include regularly in these meetings discussion or action items on program improvement.

A flowchart of our program improvement process is shown in Figure 4. Included is a list of typical departmental activities as well as a timeline for administration of assessment tools. The only new element is the Program Review Meeting. The objectives of this meeting are to review the results of the assessment analyses, to recommend improvement strategies based on the results, and to prioritize the recommendations. The Program Review Meeting involves at least one representative from each of our major constituent groups. The outcomes of the meeting are forwarded to department faculty and to the industrial advisory board for recommendations and implementation.

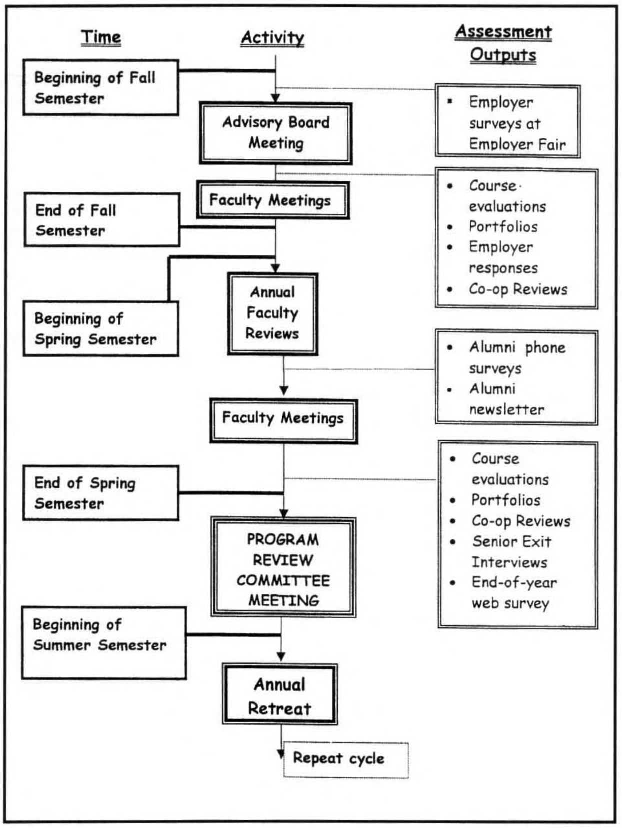


Figure 4. *Program improvement process and assessment timeline.*

<u>*Increasing Participation*</u> During our program's planning process, the sphere of constituency involvement gradually expanded. Individual faculty were given the responsibility for describing the strategies by which program objectives were achieved and outcomes demonstrated in his or her course. This naturally led to the development of course learning objectives as a set of benchmarks toward the achievement of program objectives.

Later in the process, the chairperson and faculty contributed to writing the self-study report; several faculty members were directly involved in the design and implementation of survey instruments. This involvement encouraged faculty to become more knowledgeable not only about the contents of the self-study, but also about the practical aspects of executing the processes required by EC 2000.

Members of the industrial advisory board (employers, alumni, and advisors) were involved in development of the program-improvement process through the regularly scheduled meetings of this body where the program's educational objectives were discussed and approved. Board members gave recommendations on best practices for surveying and assessment. Regular reports to the board from the chairperson and the ABET coordinator kept the group apprised of EC 2000 activities in the department.

Students were familiarized with our program's educational objectives and with course learning objectives and expected outcomes. More than just being mentioned at the beginning of the course, learning objectives and expected outcomes were integrated into the classroom culture. Learning objectives were used to chart progression of the course material; student portfolios required student self-assessment in achievement of outcomes. We also involved our students in administration of the phone survey and in analysis of the survey results. Other institutions have involved students directly in survey design. ABET program evaluators will undoubtedly find that interviews with students will give a strong indication of their involvement in program improvement.

At some point, the assessment results may suggest changes that require involvement of supporting departments (*e.g.,* chemistry, physics, mathematics). Whether this interaction occurs at the college or program level may be decided by the extent of the needed change and whether one or more engineering programs are involved. At MSU, an inter-college committee was established to address the relevance of the statistics course taken by most engineering students—this served to benefit the entire college. On the other hand, a few chemical engineering faculty collaborated with their counterparts in chemistry to discuss the restructuring of a physical chemistry sequence. Both approaches can be effective.

<u>*Who To Tell?*</u> Olds and Miller[16] emphasize the importance of reporting back to constituencies. Not only should constituencies be involved in the program-improvement processes, but they should also be made aware of the results of which they have been a part. Positive results catalyze "buy-in."

As is evident above, students are one of the major constituencies in our department. Without positive feedback, all that most of them see of the assessment process is the portfolios they must organize, the surveys that must be completed, and an occasional reference to something called an "abet"! It is gratifying to be able to come to students and say, "We are emphasizing this material in class this year because last year's graduates felt that it was a weakness in our curriculum," or "This course is being offered to help you develop more of the skills that your future employers think are vital."

Positive results of improvement efforts are also a good motivator for faculty commitment. Our initial use of student portfolios yielded good feedback to faculty. Although initially viewed as burdensome, portfolios were adopted by the faculty as a major means of outcomes assessment.

Off-campus constituencies should also be informed of the results of their feedback through existing channels such as reports to alumni through newsletters, meetings with advisory board members, and regular communication with employers. Keeping alumni and industrial representatives informed as to how their feedback is being used for program improvement can help encourage continued involvement and can engender a sense of "connectedness" to the program.

THE SITE VISIT

Having presented an example scenario for developing the EC 2000 environment and preparing for a visit, let's briefly look at the other side of the fence.

Questions and Answers Even though EC 2000 evaluators are all trained with similar materials, they will approach a site visit with different predispositions. This is one thing that has not changed from evaluation under the present ("old") criteria. But for EC 2000, all evaluators and team chairs will be looking for answers to several questions:

- What are the program objectives?
- Are program objectives linked to appropriate outcomes?
- Are the program outcomes (and therefore objectives) being met?
- Are the ABET EC 2000 defined outcomes (Criterion 3, a-k) being achieved within the context of program outcomes? Is there evidence to support this?
- What processes are in place for enhancing the program? Is the process improvement loop working and ongoing?
- Are the constituencies involved? Is there evidence to support this?

How much do members of the constituency groups know about these topics? Faculty should be familiar with these elements and should have taken some part in their realization. Students should also be familiar with objectives both at the program and the course levels, and they should know that certain outcomes are expected of a graduate of the program. Both faculty and students should be able to describe their participation in the processes and actions that have been taken to improve the program. The evaluator will most likely conduct interviews with faculty and students (and possibly with other constituencies as well) that will provide a clear indication of the level of implementation and the level of commitment to the program improvement processes.

Self-Study "Must-Have's" The self-study report is still the first contact that an evaluator has with a program. Based on the experiences of the five EC 2000 pilot schools and their evaluation teams, a better perspective has been gained on how self-studies can be most informative. The Self-Study Instructions are now considerably more prescriptive to allow for more consistent evaluation among programs. The topics they delineate are also a useful guideline for preparation for an EC 2000 visit.

It is no longer the responsibility of the evaluator to pore over course material to sift out evidence in support of a program's claims. Evidence of ongoing processes and documentation of outcomes should be clearly laid out in the self-study and in materials presented at the time of visit. It is the responsibility of the program to provide documentation of the capabilities of their students and graduates. Programs must be able to identify both the strategies used to achieve outcomes and the evidence that substantiates the success of these efforts.

In conclusion, effective use of a combination of existing assessment practices and involvement of a broad base of constituencies are the key elements in building an effective EC 2000 environment in engineering colleges. While implementation of program-improvement processes requires significant resources, the resulting program improvements are evident in a surprisingly short term and, in the long term, hold promise for keeping pace with the demands of the engineering profession.

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ASEE Annual Conference & Exposition

Charlotte, N.C.

June 20 - 23, 1999

WORKSHOPS

0213 - LabVIEW for Chemical and Mechanical Labs - Sunday

Jim Henry, Charles Knight

University of Tennessee-Chattanooga

0214 - Green Engineering Curriculum Development - Sunday

David Allen, David Shonnard

University of Texas, Michigan Technological University

TECHNICAL SESSIONS

1313 - Promoting & Rewarding Effective Teaching - Monday

- ***Promoting and Rewarding Effective Teaching***
  Richard Felder, Rebecca Brent, Douglas Hirt, Debi Switzer, Siegfried Holzer
  North Carolina State University, Clemson University, Virginia Tech

1613 - Innovative ChE Experiments and Demos - Monday

- ***A Heat Exchanger as a Student Design Project***
  M. Mavromihales
  University of Huddesfield
- ***Experiments to Accompany a First Engineering Thermodynamics Course***
  T. Scott, John O'Connell
  University of Virginia
- ***Cost Effective Experiments in Chemical Engineering Core Courses***
  Stewart Slater, Robert Hesketh
  Rowan University
- ***Classroom Demonstrations of Separation Process Principles***
  Keith Schimmel
  North Carolina A&T State University
- ***Introduction of Process Dissection into the Undergraduate Laboratory***
  Robert Ybarra
  University of Missouri-Rolla

2213 - Revitalizing Traditional ChE Courses I - Tuesday

- ***ChE Fundamentals Course - Better Learning Through Computer-Based Delivery***
  Billy Crynes
  University of Oklahoma
- ***Using Your Unit Operations Lab***
  Valerie Young • *Ohio University*
- ***The Vertical Integration of Design in Chemical Engineering***
  Ronald Gatehouse, George Selembo Jr., John McWhirter
  Pennsylvania State University
- ***Group Projects-Based Final Exams: A Novel Approach to Integrate Fundamentals and Practical Applications***
  Pedro Arce • *Florida State University*
- ***Raising the Level of Questioning in the Undergraduate ChE Curriculum***
  Anthony Muscat
  University of Arizona

2313 - Revitalizing Traditional ChE Courses II - Tuesday

- ***The Evolution of Engineering - Incorporating Biology into Traditional Engineering Curriculum***
  Jennifer Maynard, Anneta Razatos
  University of Texas
- ***Catalytic Oxidation Experiment for Chemical Reaction Engineering***
  Robert Hesketh, Stewart Slater
  Rowan University
- ***A Real-Time Approach to Process Control Education***
  William Svrcek, Donald Mahoney, Brent Young
  University of Calgary and Hyprotech
- ***Structured Trouble-Shooting in Process Design***
  Anthony Vigil, Dendy Sloan, Ron Miller
  Colorado School of Mines

2513 - Getting the Best Students to Enter ChE - Tuesday

- ***Role of the Honor Program in the Attraction and Retention of the Brightest and the Best ChemE Students***
  Pedro Arce • *Florida State University*
- ***The Promise of Silver and Gold: Not the Only Way to Attract and Retain a Devoted Miner***
  Robert Ybarra, Douglas Ludlow
  University of Missouri-Rolla
- ***How to Attract Top Students to a Chemical Engineering Program - The Experience at NJIT***
  Dana Knox, Reginald Tomkins
  New Jersey Institute of Technology

- ◧ ***Outreach and Recruitment to Attract Students to Chemical Engineering***
  Robert Hesketh, Stephanie Farrell, Zenaida Keil, James Newell
  Rowan University

<u>3213 - Process Safety in the ChE Curriculum - Wednesday</u>

- ◧ ***Teaching Chemical Process Safety: A Separate Course Versus Integration into Existing Courses***
  Anton Pintar
  Michigan Technological University
  • *Panel Discussion*

<u>3513 - ABET 2000: Improving ChE Education? - Wednesday</u>

- ◧ ***Preparing for the First ABET Accreditation Visit under Criteria 2000***
  Gary Patterson
  University of Missouri-Rolla
- ◧ ***A Process for Developing and Implementing an Assessment Plan in ChE Departments***
  James Newell, Heidi Newell, Thomas Owens, John Erjavec, Rashid Hasan, Steven Sternberg
  Rowan University and University of North Dakota
- ◧ ***Performance Assessment of EC-2000 Student Outcomes in the Unit Operations Laboratory***
  Ron Miller, Barbara Olds
  Colorado School of Mines
- ◧ ***Development of a Dynamic Curriculum Assessment Examination***
  John Wagner, David Finley
  Tri-State University
- ◧ ***Developing an Assessment Plan to Meet ABET EC 2000***
  Anton Pintar, Besty Aller, Tony Rogers, Kirk Schulz, David Shonnard
  Michigan Technological University
- ◧ ***Round 1: The Curricular Aftermath***
  Dennis Miller, Daina Briedis
  Michigan State University

<u>3613 - Innovative Uses of Computers in ChE - Wednesday</u>

- ◧ ***Implementing Computational Methods into Classes Throughout the Undergraduate Chemical Engineering Curriculum***
  William Perry, Victor Barocas, David Clough
  University of Colorado
- ◧ ***Laptop Computers and Curricula Integration***
  Jerry Caskey
  Rose-Hulman Institute of Technology
- ◧ ***Integrating Research Into The Undergraduate Curriculum - NASA's Microgravity Bioreactor***
  Shani Francis, Keith Schimmel, Neal Pellis
  North Carolina A&T State University and NASA
- ◧ ***A Phenomena-Oriented Environment for Teaching Process Modeling: Novel Modeling Software and Its Use in Problem Solving***
  Alan Foss, Kevin Geurts, Peter Goodeve, Kevin Dahm, George Stephanopoulos, Jerry Bieszczad, Alexandros Koulouris
  University of California, Berkeley and Massachusetts Institute of Technology
- ◧ ***Teaching Material and Energy Balances on the Internet***
  Alec Scranton, Randy Russell, Nicholas Basker, Lisa Scranton
  Michigan State University
- ◧ ***Virtual Laboratory Accidents Designed to Increase Safety Awareness***
  John Bell, Scott Fogler
  University of Michigan

OTHER SESSIONS

<u>1113 - ChE Div. Executive Committee Meeting/Breakfast - Monday Morning</u>

<u>1413 - ChE Chairpersons Luncheon - Monday</u>

This luncheon meeting will provide an opportunity for department chairpersons to exchange ideas and information about issues relevant to chemical engineering. The meeting will open with a discussion of the following issues: enrollment, placement, accreditation, and new curricular trends.

<u>1713 - ChE Division Reception/Mixer Sponsored by the CACHE Corporation- Monday Evening</u>

<u>2613 - Union Carbide Lectureship Award Presentation - Tuesday Afternoon</u>

- ◧ **Particle Dynamics in Fluidization and Fluid-Particle Systems**
  Dr. L. S. Fan • *The Ohio State University*

<u>2713 - Chemical Engineering Division Dinner - Tuesday Evening</u>

<u>3413 - ChE Div. Business Meeting/Luncheon - Wednesday</u>

More information about the 1999 ASEE Annual Conference & Exposition can be found at
http://www.asee.org/conferences/annual99/

Random Thoughts . . .

MEMO

TO: *Students Who Are Disappointed With Their Last Test Grade*

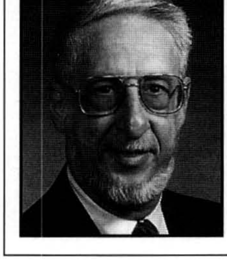
FROM: *R.M. Felder*

North Carolina State University
Raleigh, NC 27695

Dear Students:

Many of you have told your instructor that you understood the course material much better than your last test grade showed, and some of you asked what you should do to keep the same thing from happening on the next test.

Let me ask you some questions about how you prepared for the test. Answer them as honestly as you can. If you answer "No" to many of them, your disappointing test grade should not be too surprising. If there are still a lot of "No"s after the next test, your disappointing grade on that test should be even less surprising. If your answer to most of these questions is "Yes" and you still got a poor grade, something else must be going on. It might be a good idea for you to meet with your instructor or a counselor to see if you can figure out what it is.



***Richard M. Felder** is Hoechst Celanese Professor of Chemical Engineering at North Carolina State University. He received his BChE from City College of CUNY and his PhD from Princeton. He has presented courses on chemical engineering principles, reactor design, process optimization, and effective teaching to various American and foreign industries and institutions. He is coauthor of the text* Elementary Principles of chemical Processes *(Wiley, 1986).*

You'll notice that several of the questions presume that you're working with classmates on the homework—either comparing solutions you first obtained individually or actually getting together to work out the solutions. Either approach is fine. In fact, if you've been working entirely by yourself and your test grades are unsatisfactory, I would strongly encourage you to find one or two homework and study partners to work with before the next test. (Be careful about the second approach, however; if what you're doing is mainly watching others work out problems you're probably doing yourself more harm than good.)

The question "How should I prepare for the next test" becomes easy once you've filled out the checklist. The answer is . . .

> *"Do whatever it takes to be able to answer 'Yes' to most of the questions."*

Good luck,
Richard Felder

Test Preparation Checklist

Answer yes if you did these things regularly, not just occasionally.

Homework

1. Did you make a serious effort to read and understand the text? (Just hunting for worked-out examples exactly like the homework problems doesn't count.)	____ Yes	____ No
2. Did you work with classmates on homework problems, or at least check your solutions with others?	____ Yes	____ No
3. Did you attempt to outline every homework problem solution before working with classmates?	____ Yes	____ No
4. Did you participate actively in homework group discussions (contributing ideas, asking questions)?	____ Yes	____ No
5. Did you consult with the instructor or teaching assistants when you were having trouble with something?	____ Yes	____ No
6. Did you understand ALL of your homework problem solutions when they were handed in?	____ Yes	____ No
7. Did you ask in class for explanations of homework problem solutions that weren't clear to you?	____ Yes	____ No

Test preparation

8. Before the test, did you carefully go through the study guide and convince yourself that you could do everything on it?	____ Yes	____ No
9. Did you attempt to outline lots of problem solutions quickly, without spending time on the algebra and calculations?	____ Yes	____ No
10. Did you go over the study guide and problems with classmates and quiz one another?	____ Yes	____ No
11. Did you attend the review session before the test and ask questions about anything you weren't sure about?	____ Yes	____ No
12. Did you get a reasonable night's sleep before the test? (If your answer is no, your answers to 1-11 may not matter.)	____ Yes	____ No
TOTAL	____ **Yes**	____ **No**

The more "Yes" responses you recorded, the better your preparation for the test. If you recorded two or more "No" responses, think seriously about making some changes in how you prepare for the next test.

All of the *Random Thoughts* columns are now available on the World Wide Web at
http://www2.ncsu.edu/effective_teaching/ and at http://che.ufl.edu/~cee/

Important Concepts in Undergraduate KINETICS AND REACTOR DESIGN COURSES

JOHN L. FALCONER, GARY S. HUVARD*
University of Colorado • Boulder, CO 80309-0424

Most chemical engineers will never *design* a reactor; they will, however, often be in a position to *specify* a reactor type, size, material, and design. Or, they will be asked to analyze an existing reactor to 1) fit a new reaction at a required production rate into the reactor, or 2) improve product quality, or 3) determine how to squeeze more production from the reactor without spending much money, adversely affecting the product, or blowing anything up.

Most industrial chemical reactions are scaled up and put into production without detailed knowledge of the chemical kinetics and physical chemistries that affect the reactions. Quite often, reaction engineers must design using instinct, an understanding of how other, similar systems behave, and a proper application of the important concepts related to reactor design. We present a concise list of important kinetics, thermodynamics, reactor design concepts, rules-of-thumb, and applications that chemical engineering undergraduates need for entry-level industrial positions or to start graduate studies. Most are from texts widely used in undergraduate courses.[1-5] Although many other aspects of kinetics and reactor design are arguably as important for particular problems, our list should serve as a solid foundation for attacking the types of problems typically encountered by recent graduates.

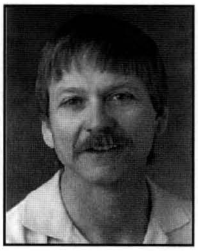
Successfully teaching undergraduates to remember the points below is only half the battle. We want them to be able to *do* things with the information—analyze, design, specify, simulate, estimate, explain, etc. Felder and Brent[6] discussed the use of instructional objectives as a route to incorporating higher-level thinking skills into undergraduate courses. They differentiate between simply listing course topics in a syllabus and writing proactive objectives that teach students to apply the factual information to problems. In a forthcoming paper, we will use the list as a starting point for a set of instructional objectives for an undergraduate kinetics and reaction engineering course.

* *Address: Huvard Research and Consulting, Inc., 12218 Prince Philip Lane, Chesterfield, VA 23838*

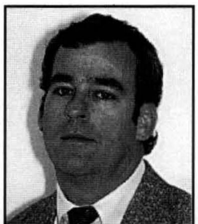
THERMODYNAMICS

1. Thermodynamics does not predict kinetics. A more negative, free-energy change (*i.e.,* a larger equilibrium constant) does *not* imply a faster reaction rate.
2. Catalysts can only increase the rate of processes that are thermodynamically favored; they cannot initiate reactions that are not thermodynamically feasible. A catalyst does not change ΔG, ΔH, or the equilibrium constant.
3. Three of the most important calculations for a reactor are

- *Adiabatic temperature:* if the heat released for an exothermic reaction is not removed, this temperature will be attained at complete conversion
- *Equilibrium* composition: no reactor can produce



John L. Falconer *is Professor of Chemical Engineering at the University of Colorado. He received a BES from the Johns Hopkins University and his PhD from Stanford University. His research interests are in heterogeneous catalysis, photocatalysis, and zeolite membranes for separations.*



Gary S. Huvard *earned his BS in chemistry from Campbell College and his PhD in chemical engineering from North Carolina State University. He spent eight years with the Corporate Research Group at BFGoodrich and three years with du Pont's Tyvek Technical organization before establishing a private practice in 1989.*

yields of products beyond those predicted by equilibrium, but we can often choose which reactions to consider in the equilibrium calculations (see below).

- *Isothermal heat load:* heat must be removed (added) at the same rate at which it is generated (consumed) by reaction to keep a reactor isothermal.

4. As temperature increases for an exothermic reaction, equilibrium conversion decreases. For an endothermic reaction, equilibrium conversion increases.

We present a concise list of important kinetics, thermodynamics, reactor design concepts, rules-of-thumb, and applications that chemical engineering undergraduates need for entry-level industrial positions or to start graduate studies. . . . our list should serve as a solid foundation for attacking the types of problems typically encountered by recent graduates.

KINETICS: RATE LAWS AND MECHANISMS

1. As long as a reaction is not limited by equilibrium or mass transfer, then longer reaction times, higher temperature, and more catalyst all increase conversion. A reaction that takes place in one hour at 200°C could take place in less than one second at 400°C. There are exceptions for certain ionic polymerization reactions (negative apparent activation energies).
2. The rate of reaction is often the product of a rate constant, which *usually* increases exponentially with temperature (relatively few reaction rates decrease with temperature) and reactant concentrations raised to some power. The activation energy is the term in the exponential that determines how fast the rate increases with temperature.
3. Most chemical processes involve multiple reactions. Higher temperatures increase selectivity for reactions with higher activation energies. Higher reactant concentrations increase selectivity for reactions with higher reaction orders.
4. Local concentrations determine reaction rates (*e.g.,* if an insoluble solid product forms from a *pure* liquid reactant, the *concentration* of reactant does not change).
5. The steady-state approximation can be applied to a series of reaction steps by assuming that all reaction steps proceed at the same rate.
6. The rate-determining step in a series of reaction steps is the step furthest from equilibrium, and all the other steps are assumed to be in quasi-equilibrium.
7. For homogeneous reactions, rates are proportional to volume. In contrast, for heterogeneous reactions, rates are proportional to *surface area* (interphase area or catalyst surface area before deactivation).

DETERMINATION OF RATE PARAMETERS

1. A kinetic rate expression cannot reliably be extrapolated outside the concentration, conversion, or temperature regime where the data were obtained.
2. For an uncatalyzed reaction, the rate law (rate constant, activation energy, order of reaction) is an intrinsic property of the reaction and *not* the reactor. For a catalyzed reaction, the rate law changes when the catalyst is changed.
3. For a first-order, isothermal reaction, fractional conversion (X) depends on time but *not* the initial concentration: $X=1-e^{-kt}$. Thus, half life ($t_{1/2}$: the time for X=0.5) contains the same information as the rate constant (k). $t_{1/2}=(\ln 2)/k$
4. A reaction mechanism can be suggested, but *not* proven, by fitting data to a rate expression derived from a reaction sequence.
5. Rate parameters can be determined from experimental kinetic data (conversion versus time) in batch or plug flow reactors by the methods of integration and differentiation. The method of integration, which makes use of data in integrated form, is preferred over the method of differentiation (which exacerbates the impact of experimental error). If rates are determined, regression can be used to determine the rate parameters.

MATERIAL AND ENERGY BALANCES

1. Material balances on *individual* components are most useful for reactor design:

Accumulation(±) = In(+) - Out(+) + Generation by reaction(±)

2. For systems with multiple reactions, at least as many material balances should be solved as the number of independent reactions, but a material balance can be solved for every component in the system.
3. The first law of thermodynamics applies to reactors, both closed and open systems, and is used to determine reactor temperature:

$$dU/dt = \sum_i (F_i H_i)_{in} - \sum_i (F_i H_i)_{out} + Q - W$$

where U is the total internal energy of the system, F_i is the molar flow rate into or out of the reactor of a given component, H_i is the enthalpy per mole of a given component at inlet or outlet conditions (the heat of reaction is contained in these terms), Q is the heat added per time, and W is the work done by the system per time.

4. For reactions where the heat of reaction is independent of temperature, the temperature change in an adiabatic reactor is proportional to the conversion.
5. In viscous reaction systems, heat developed by agitator work is often an important term in the energy balance.

IDEAL AND REAL REACTORS

1. Except for an ideal plug flow reactor (PFR), not all molecules spend the same amount of time in a flow reactor, and the residence time distribution can affect both rate and selectivity.
2. The material balances for batch reactors (BR) and ideal PFRs are mathematically equivalent; time in a BR is equivalent to residence time in an ideal PFR.
3. Material entering an ideal continuous stirred tank reactor (CSTR) undergoes a step change in concentration and temperature. An ideal CSTR operates at the exit temperature and concentrations.
4. Although all reaction occurs in an ideal CSTR at constant concentration and temperature, molecules flowing through both ideal and real CSTRs have a broad distribution of residence times. The residence time distribution of an ideal CSTR is exactly known.
5. CSTRs are often used in series to decrease the average residence time required for a given conversion (relative to a single, large CSTR) or to narrow the residence time distribution to one closer to that of a PFR.
6. Reactor temperature and concentrations can be sensitive to feed conditions. Reactor behavior is nonlinear because of the exponential Arrhenius rate constant, and reactors are the most likely equipment in a plant to explode.
7. For an exothermic reaction in a nonisothermal CSTR ($t_{feed} \neq t_{reactor}$), multiple steady states can exist (*i.e.,* the material and energy balances have multiple solutions). Multiple steady states are the result of energy feedback and the nonlinear behavior of the rate constant. This can result in an unstable operating condition leading to a quench (the reaction stops) or a runaway (the reactor overheats). Either situation can be dangerous and is to be avoided.
8. Reactor tank volume, and thus heat generated for a homogeneous exothermic reaction, increases as the cube of the reactor dimension, but heat transfer through the external surface increases only as the square, so temperature control is much more difficult for larger reactors without internal cooling coils. For exothermic reactions in jacketed reactors, an upper limit on reactor volume exists. If the reaction is carried out in a reactor larger than this, the heat cannot be removed as fast as it is generated without other means for cooling.
9. For gas-phase reactions, when the number of moles changes due to reaction, the concentration of reactants changes as a result, and flow rates and reaction rates also change.
10. For series reaction, the more important variable is space time or reaction time, and for positive-order kinetics, higher selectivity to an intermediate is obtained in a PFR than in a CSTR.

CATALYSIS

1. A catalyst usually lowers the activation energy for reaction.
2. The three most important attributes of a catalyst are selectivity, activity, and stability. Often, selectivity is the most important attribute.
3. All catalysts eventually deactivate, usually due to a loss of catalytic sites.
4. A catalyst does more than allow a system to achieve its most thermodynamically stable state; it can selectively accelerate a desired reaction. In the majority of industrial processes, the products are not those expected from equilibrium conversion for all reactions.
5. Many industrial reactions are limited by diffusion (mass- transfer limited). Concentration gradients external to a catalyst particle are determined from mass-transfer coefficient correlations. Concentration gradients within a porous catalyst particle are accounted for by an effectiveness factor.
6. If a catalyst increases the rate constant of a forward reaction, it also increases the rate constant of the reverse reaction (microscopic reversibility).

MIXING

1. Whenever reaction rates are of the same magnitude as, or faster than, the mixing rate in a stirred reactor, mixing will have a serious impact on results. Poor mixing is a primary source of variability in products made in batch reactors. The results for a reaction run in a poorly mixed CSTR may deviate strongly from those expected.
2. There is no single "correct" agitator type. Different agitator designs may perform equally well (or equally poorly) for a given application. Although some

detailed design calculations can be carried out, workable designs are often developed by trial and error.

3. Many reactions involve shear-sensitive materials, which severely limit the maximum mixing rate and make impeller and reactor design important. Mixing becomes the limiting factor (see item #1).

THE REAL WORLD

1. Real processes involve multiple reactions with multiple heat effects.
2. Most industrial chemical reactions are exothermic and heat transfer is often the most important design criteria.
3. Most bioreactions can only be carried out within a narrow temperature range. Generally, these reactions are relatively non-energetic and temperature control is easily achieved. Like other heterogeneous reactions, mass transfer is usually the most important design criteria.
4. The largest number of different chemical reactions (but not the largest quantity of material) are run in batch reactors, which are especially common in the pharmaceutical, biotech, polymer, and cosmetics industries. Sizes vary from a few liters to over 200,000 liters.
5. CSTRs are the next most common reactors, followed by PFRs and then by hybrid reactor types (fluidized beds, transport beds, trickle beds).
6. Continuous catalytic reactors are common in the petrochemical industries and, by far, the largest quantities of materials are produced in these types of reactors.

ACKNOWLEDGMENTS

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ChE *letter to the editor*

Dear Editor:

In the recent paper titled "Permeation fo Gases in Asymmetric Ceramic Membranes" [*CEE*, **33**(1), p. 58 (1999)], by C. Finol and J. Coronas, there was an error in the equation used to calculate the Knudsen number. The correct equation for this clculation is:

$$Kn = \frac{\lambda}{r}, \quad \lambda = \frac{16\,\mu}{5\,\pi P}\sqrt{\frac{\pi RT}{2\,M}}$$

where all the parameters employed in the equation were already defined in the mentioned article. We apologize for any trouble that this mistake may have caused.

Thank you for your consideration.

C. Finol
J. Coronas
University of Zaragoza
50009 Zaragoza, Spain

A New Approach To TEACHING TURBULENT FLOW

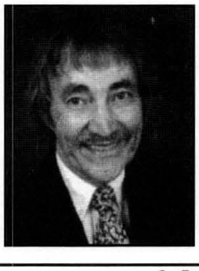
STUART W. CHURCHILL
University of Pennsylvania • Philadelphia, PA 19104-6393

Turbulent flow, although the most important regime in practice, is often given short shrift in textbooks on fluid mechanics, and thereby in the classroom, at both the undergraduate and graduate levels, because its theoretical structure is less developed than that for potential, creeping, and laminar flows. Furthermore, recent analyses have shown that much of that limited theoretical structure is unsound, and in addition recent computational and experimental advances have identified significant errors in the predictions of the generally accepted correlating equations in current textbooks and handbooks.

The objective of this article is to provide a supplement for the teacher that summarizes some of the more important recent work in turbulent flow and describes the present state of the art in a form suitable for the classroom. In the interests of brevity, the actual derivations are limited to fully developed flow in a round tube, but the methodologies are directly applicable for parallel-plate channels and circular annuli and are readily adapted for unconfined flow along a flat plate. The details of some of the derivations are purposely omitted in order to provide relevant and constructive material for homework assignments.

In recognition of the highly variable allotments of time for this subject and the different inclinations of individual teachers, a discussion of each of the following topics is presented separately after the main development:

- *The implicit as well as the explicit idealizations and postulates that are inherent in the new "exact" structure*
- *The sources and reliability of the individual terms, coefficients, and exponents in the several new correlating equations*
- *The concepts and expressions in current textbooks and handbooks that are to be eliminated or at least identified as false or obsolete*



Stuart W. Churchill *is the Carl V.S. Patterson Professor Emeritus at the University of Pennsylvania, where he has been since 1967. His BSE degrees (in ChE and Math), MSE, and PhD were all obtained at the University of Michigan, where he also taught from 1950-1967. Since his formal retirement in 1990, he has continued to teach and carry out research on heat transfer and combustion. He is also currently completing a book on turbulent flow.*

RECENT DEVELOPMENTS

The advances in the description of turbulent flow under consideration herein are:

1. *The proposal by Churchill and Chan*[1] *to use the dimensionless turbulent shear stress rather than the eddy viscosity or the mixing length as a correlating variable.*
2. *The precise determination of the turbulent shear stress near the walls of a parallel-plate channel by Kim, et al.,*[2] *Lyons, et al.,*[3] *Rutledge and Sleicher,*[4] *and others by means of DNS (direct numerical simulations).*
3. *The development by Churchill and Chan*[5] *of a generalized correlating equation for the turbulent shear stress for the complete cross-section of a parallel-plate channel or a round tube.*
4. *The computation by Churchill and Chan*[5,6] *of improved numerical values for the velocity distribution and the friction factor using this correlation, and their development of generalized correlating equations for these values.*
5. *The experimental determination by Zagarola*[7] *of improved and extended values for the velocity distribution and the pressure gradient in a round tube.*
6. *The slight but significant modification by Churchill*[8] *of the correlating equations of Churchill and Chan*[5,6] *for the turbulent shear stress, the velocity distribution, and the friction factor for a round tube on the basis of these new experimental values.*

Development of a New Integral Structure for Turbulent Flow

Time-averaging the differential equations for the conservation of momentum in polar cylindrical coordinates for a Newtonian fluid with invariant physical properties (to be found, for example, in Bird, *et al.*,[9]) and then specializing that result for steady, fully developed flow in a round tube leads to

$$-\frac{\partial P}{\partial r}-\frac{1}{r}\frac{d}{dr}\left(\rho r\,\overline{u_r'u_r'}\right)+\frac{\rho\left(\overline{u_\theta'u_\theta'}\right)}{r}=0 \tag{1}$$

$$\frac{1}{r}\frac{d}{dr}\left(r\,\overline{u_r'u_\theta'}\right)+\frac{\overline{u_r'u_\theta'}}{r}=0 \tag{2}$$

and

$$-\frac{\partial P}{\partial z}+\frac{1}{r}\frac{d}{dr}\left(\mu r\frac{du_z}{dr}-\rho r\,\overline{u_r'u_z'}\right)=0 \tag{3}$$

where here P is the dynamic pressure that arises from changes in velocity only. Analytical integration of these three expressions with respect to r results in

$$P=P_w-\rho\,\overline{u_r'u_r'}-\rho\int_r^a\left(\overline{u_\theta'u_\theta'}-\overline{u_r'u_r'}\right)\frac{dr}{r} \tag{4}$$

$$\overline{u_r'u_\theta'}=0 \tag{5}$$

and

$$\frac{r}{2}\left(-\frac{\partial P}{\partial z}\right)=-\mu\frac{du_z}{dr}+\rho\,\overline{u_r'u_z'} \tag{6}$$

Equation 4 provides an expression for the radial variation of pressure, and Eq. 5 indicates that the *Coriolis* force is zero at all radii. Equation 6 serves as the starting point for all subsequent derivations. (The details of the derivations of Eqs. 1 through 6 as well as the calculation of the pressure drop across the tube (using the experimental data of Laufer[10]) are suggested as homework.)

For convenience in subsequent manipulations, Eq. 6 may be re-expressed as follows in terms of y=a-r, $u=u_z$, $v=u_y=-u_r$, and $\{\tau_w[1-(y/a)]\}=\tau=(r/2)[-(dP/dz)]$:

$$\tau_w\left(1-\frac{y}{a}\right)=\mu\frac{du}{dy}-\rho\,\overline{u'v'} \tag{7}$$

Suggested Exercises: Show that

$$\tau_w\left(1-\frac{y}{a}\right)=\tau=\frac{r}{2}\left(-\frac{\partial P}{\partial z}\right)$$

and prove that

$$\frac{\partial P}{\partial z}=\frac{dP}{dz}$$

Equation 7 may in turn be expressed in the following dimensionless form for simplicity and convenience:

$$\left(1-\frac{y^+}{a^+}\right)\left[1-\left(\overline{u'v'}\right)^{++}\right]=\frac{du^+}{dy^+} \tag{8}$$

where here $y^+=y(\tau_w\rho)^{1/2}/\mu$, $a^+=a(\tau_w\rho)^{1/2}/\mu$, $u^+=u(\rho/\tau_w)^{1/2}$, and $\left(\overline{u'v'}\right)^{++}=-\rho\overline{u'v'}/\tau$. The first three of these four dimensionless quantities were defined by Prandtl[11] in 1926, while the fourth, which has physical significance as the fraction of the local shear stress due to turbulence, was first defined by Churchill[12] in 1997.

Equation 8 may be integrated formally to obtain

$$u^+=\int_0^{y^+}\left[1-\left(\overline{u'v'}\right)^{++}\right]\left(1-\frac{y^+}{a^+}\right)dy^+ \tag{9}$$

$$=\frac{a^+}{2}\int_{R^2}^{1}\left[1-\left(\overline{u'v'}\right)^{++}\right]dR^2 \tag{10}$$

$$=\frac{a^+}{2}\left(1-R^2\right)-\frac{a^+}{2}\int_{R^2}^{1}\left(\overline{u'v'}\right)^{++}dR^2 \tag{11}$$

where $R=r/a=1-(y^+/a^+)$. The form of Eq. 11 reveals that the contribution of the turbulent fluctuations to the velocity distribution may be expressed as a simple deduction from the expression for purely laminar flow at the same value of a^+. The initial form of Eq. 9 in terms of y^+, however, proves to be more convenient for numerical calculations.

The integration of a^+ from Eq. 10 over the cross-section to obtain the mixed-mean value may be expressed as

$$u_m^+=\int_0^1 u^+dR^2=\int_0^1\left(\int_{R^2}^1\left[1-\left(\overline{u'v'}\right)^{++}\right]dR^2\right)dR^2 \tag{12}$$

which may be integrated by parts to obtain

$$u_m^+=\frac{a^+}{4}\int_0^1\left[1-\left(\overline{u'v'}\right)^{++}\right]dR^4=\frac{a^+}{4}-\frac{a^+}{4}\int_0^1\left(\overline{u'v'}\right)^{++}dR^4 \tag{13}$$

$$=\int_0^{a^+}\left[1-\left(\overline{u'v'}\right)^{++}\right]\left(1-\frac{y^+}{a^+}\right)^3dy^+ \tag{14}$$

The right-most form of Eq. 13 reveals that the contribution of the turbulent fluctuations to the mixed-mean velocity is also a deduction from the expression for purely laminar flow at the same value of a^+. The formulation in terms of y^+, namely Eq. 14, again proves to be the most convenient for numerical calculations.

(The detailed derivation of Eq. 13 from Eq. 10 is suggested as an exercise.)

Since the Fanning friction factor is defined by

$$f \equiv \frac{2\,\tau_w}{\rho u_m^2} = \frac{2}{\left(u_m^+\right)^2} \tag{15}$$

Eqs. 13 and 14 may be interpreted as expressions for the evaluation of $(2/f)^{1/2}$ and hence of f.

Churchill[8] recently proposed the following generalized correlating equation for $\left(\overline{u'v'}\right)^{++}$ for use in Eqs. 9 and 14 for $a^+ > 300$:

$$\left(\overline{u'v'}\right)^{++} =$$

$$\left\{\left[0.7\left(\frac{y^+}{10}\right)^3\right]^{-\frac{8}{7}} + \left|\exp\left\{\frac{-1}{0.436y^+}\right\} - \frac{1}{0.436a^+}\left(1+\frac{6.95y^+}{a^+}\right)\right|^{-\frac{8}{7}}\right\}^{-\frac{7}{8}} \tag{16}$$

The construction of Eq. 16 is discussed subsequently.

Values of u^+ calculated from Eq. 9 using Eq. 16 for $\left(\overline{u'v'}\right)^{++}$ have been correlated by Churchill[8] with the expression

$$u^+ = \left[\left(u_0^+\right)^{-3} + \left(u_\infty^+\right)^{-3}\right]^{-\frac{1}{3}} \tag{17}$$

where

$$u_0^+ = \frac{\left(y^+\right)^2}{1 + y^+ - \exp\left\{-\frac{7}{4}\left(\frac{y^+}{10}\right)^4\right\}} \tag{18}$$

and

$$u_\infty^+ = \frac{1}{0.436}\,\ell n\left[\frac{1 + 14.48\,y^+}{1 + 0.301\left(\frac{e}{a}\right)a^+}\right] + 6.824\left(\frac{y^+}{a^+}\right)^2 - 5.314\left(\frac{y^+}{a^+}\right)^3 \tag{19}$$

and those for u_m^+ using Eqs. 14 and 16 by

$$u_m^+ = \left(\frac{2}{f}\right)^{\frac{1}{2}} = 3.30 - \frac{161.2}{a^+} + \left(\frac{47.6}{a^+}\right)^2 + \frac{1}{0.436}\,\ell n\left[\frac{a^+}{1 + 0.301\left(\frac{e}{a}\right)a^+}\right] \tag{20}$$

The term $[1+0.301(e/a)a^+]$ was arbitrarily incorporated in Eqs. 19 and 20 to extend their coverage to tubes with natural roughness e. Values of e for various types of commercial piping are tabulated in all handbooks and most textbooks on fluid flow. Of course, Eqs. 16 and 18 are inapplicable for rough pipe for values of y^+ of the order of magnitude or less of e^+. The construction of Eqs. 17 through 20 is also discussed subsequently.

The predictions of $\left(\overline{u'v'}\right)^{++}$ by the near-equivalent of Eq. 16 are compared with the computed values of Kim, et al.,[2] Rutledge and Sleicher,[3] and the experimental values of Eckelmann[13] for small values of a^+ in Figure 1 and with the experimental values of Wei and Willmarth[14] for moderate values of a^+ in Figure 2. The agreement appears to be within the scatter of the individual values. The waviness of the curves representing Eq. 16 in Figure 1 is an artifact of that expression, not an error in graphing.

> *Homework exercise:* Can such apparently anomalous behavior be rejected on physical grounds?

The slight uncertainty in $\left(\overline{u'v'}\right)^{++}$ as predicted by Eq. 16 is reduced in u^+ and u_m^+ by the integrations by means of which the latter are evaluated numerically.

> *Homework exercise:* Explain the grounds, if any, for this assertion.

The predictions of u^+ by Eqs. 17 through 19 differ no more than 0.3%, and those of u_m^+ by Eq. 20 no more than 0.1% from the very precise experimental values of Zagarola (see Churchill[8]). The use of Eqs. 17 through 19 and Eq. 20 to predict u^+ and u_m^+ respectively is more convenient than the use of Eqs. 9 and 11 by virtue of the avoidance of numerical integration and has the advantage of including an expression for the effects of roughness. However, slightly greater accuracy for smooth tubes is to be expected from Eqs. 9 and 11 with 16.

> *Homework exercise:* Why?

This completes the direct presentation of the new structure and correlating equations for fully developed turbulent flow

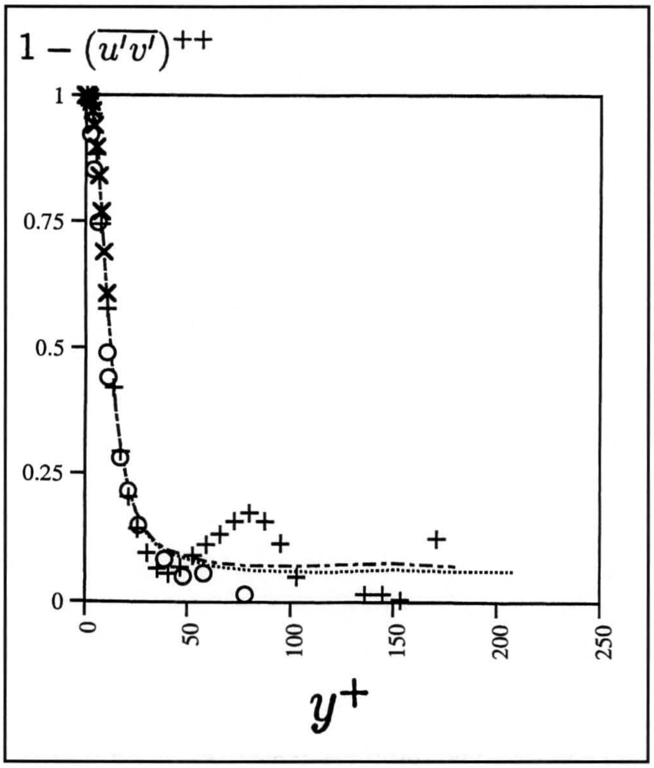


Figure 1. *Representation of experimental and numerically computed values of the dimensionless/turbulent shear stress for small y^+ by Eq. 16 (from Churchill[12]).*

in a round tube. It is important insofar as time allows, however, to discuss with the students the postulates and idealizations inherent in the above structure, to examine the sources and reliability of the terms, coefficients, and exponents of the correlating equations, and to describe the obsolete concepts and correlations that are still to be encountered in the literature of the past and perhaps even some of that of the future. The background for such discussions follows.

POSTULATES AND IDEALIZATIONS

Equations 1 through 14 are exact insofar as steady, fully developed turbulent flow is attainable, time-averaging is a valid procedure, and the effects of viscous dissipation and the variation of physical properties are negligible. The validity of these idealizations and postulates will now be briefly considered.

Although the existence of a state of fully developed turbulent flow has been questioned on theoretical grounds,[15] the close approach to such an invariant condition at a moderate distance from the inlet of the tube is well supported experimentally.[16]

The propriety of time-averaging has also been questioned by some on theoretical grounds, but no significant and practical discrepancy in the expressions obtained by this procedure has been documented experimentally.

The fluctuations in pressure with time as well as the radial and axial variations in the time-mean pressure result in proportional variations in the density of a gas, but such effects are ordinarily negligible on the mean. Viscous dissipation generates radial and axial variations in the temperature of the fluid and thereby corresponding changes in viscosity as well as in density. Such effects have, however, been found to be completely negligible for ordinary fluids and conditions.

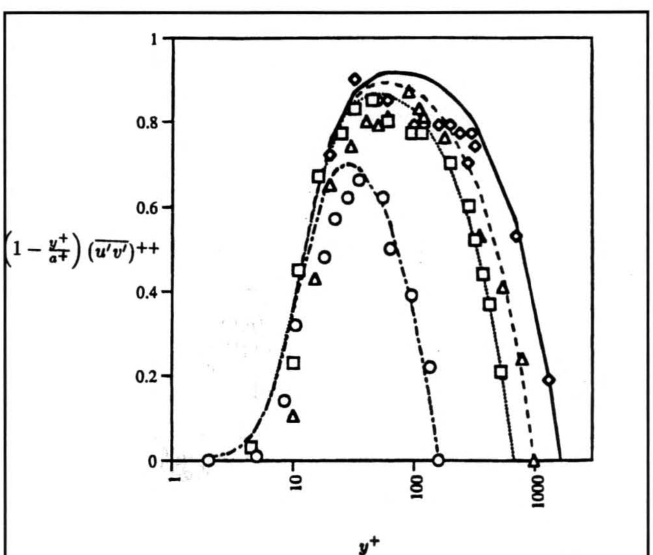


__Figure 2.__ Representation of experimental values of the dimensionless turbulent shear stress for all y^+ by Eq. 16 (from Churchill and Chan[5]).

Although this discussion implies that Eqs. 1 through 14 may be considered to be essentially exact, it also properly suggests to students that extreme conditions may be encountered for which they are not, for example, at very low pressure (hard vacuums), at very high temperatures (ionized gases), with very viscous fluids (polymers), and in fluids being heated at the wall. These expressions are also inapplicable for developing flow. The quantitative evaluation of such effects poses problems of higher order than would be appropriate in most elementary courses in fluid mechanics.

EXPERIMENTAL AND THEORETICAL BASIS FOR THE CORRELATING EQUATIONS

Since students may be expected to be confronted at various times in their career by alternatives to Eqs. 16-20, it is appropriate that they understand their source and reliability as a basis for making the correct choices and invoking appropriate safety factors.

Equations 16 and 17 both have the canonical form proposed by Churchill and Usagi,[17] namely an arbitrary power-mean of asymptotic expressions for small and large values of the independent variable. The asymptote for $\left(\overline{u'v'}\right)^{++}$ as $y \to 0$ was taken to be

$$\left(\overline{u'v'}\right)^{++} = 0.0007\left(y^+\right)^3 \tag{21}$$

Equation 21 is based on the relationship

$$\overline{u'v'} \propto y^3 \tag{22}$$

first derived by Murphree[18] by means of asymptote expansions. The dedimensionalization of the turbulent shear stress by τ rather than τ_w in Eq. 21 is arbitrary, but is much more convenient and has no subsequent adverse consequences. Equation 21 has experimental support, but even more impressive confirmation by the previously cited direct numerical simulations, which are also the primary source of the coefficient of 0.0007. This value is nevertheless somewhat uncertain and therefore subject to possible future improvement. However, any resulting consequences with respect to u^+ and u_m^+ are certain to be small.

Integration of Eq. 7 using Eq. 21 for $\left(\overline{u'v'}\right)^{++}$ results in the corresponding asymptote for u^+ as $y^+ \to 0$, namely

$$u^+ = y^+ - 0.000175\left(y^+\right)^4 - \frac{\left(y^+\right)^2}{2a^+} + \frac{0.00014\left(y^+\right)^5}{a^+} \tag{23}$$

For conditions such that the second term on the right-hand side is significant, as well as for large a^+, the third and fourth terms may be dropped. Equation 18 constitutes an arbitrary approximation for this reduced form of Eq. 23 that avoids the negative values of u^+ for large y^+ that would not be acceptable in the combined form of Eq. 17.

> The justification of these two simplifications may be assigned as exercises.

The starting point for asymptotes for $\left(\overline{u'v'}\right)^{++}$ and u^+ for $y^+ \rightarrow a^+$ is

$$u^+ = A + B\,\ell n\left(y^+\right) + C\left(\frac{y^+}{a^+}\right)^2 + D\left(\frac{y^+}{a^+}\right)^3 \qquad (24)$$

The first two terms on the right-hand side of Eq. 24 were first derived, as discussed subsequently, by Prandtl on the basis of his mixing-length model for the "turbulent core near the wall." The third and fourth terms were proposed by Churchill[19] to represent the "wake," the increased velocity with respect to the first two terms near the centerline. Churchill[8] chose A=6.13, B=1/0.436, and C-D=1.51 to fit the experimental measurements of Zagarola[7], and D=-(B+2C)/3 to force du^+/dy^+ to zero at $y^+=a^+$. This latter choice also results in the necessary asymptotic approach of $u_c^+ - u^+ \rightarrow E\left[1-\left(y^+/a^+\right)\right]^2$ as $y^+ \rightarrow a^+$. The net result is

$$u_\infty^+ = 6.13 + \frac{1}{0.436}\,\ell n\left(y^+\right) + 6.824\left(\frac{y^+}{a^+}\right)^2 - 5.314\left(\frac{y^+}{a^+}\right)^3 \qquad (25)$$

Incorporating the constant 6.13 in the argument of the logarithm, adding unity to that argument to avoid negative values of u^+ as $y \rightarrow 0$, and dividing that result by $\left[1+0.301(e/a)a^+\right]$ to incorporate the effect of roughness, then results in Eq. 19. The exponent of -3 in Eq. 17 was chosen to represent experimental velocities for intermediate values of y^+. This representation is relatively insensitive to that value.

The term within the absolute values signs of Eq. 16 was derived by differentiating Eq. 16 with respect to y^+, substituting the result in Eq. 9, dividing through by $[1-(y^+/a^+)]$, and approximating $[1-(1/0.436y^+)]$ by $\exp(-1/0.436y^+)$. The latter step and the absolute value sign are simply mathematical devices to avoid negative values of $\left(\overline{u'v'}\right)^{++}$ as $y \rightarrow 0$. The arbitrary exponent n was evaluated on the basis of the experimental data of Wei and Willmarth[14] and others for moderate and large values of a^+ and intermediate values of y^+ as well as on the basis of velocity distributions derived from Eq. 16.[5]

Equation 20 was constructed by integrating u^+ from Eq. 19 over the cross-section and adding arbitrary terms in $(a^+)^{-1}$ and $(a^+)^{-2}$ to account for the decreased velocity near the wall where $u^+ \cong y^+$. The coefficients -161.2 and 47.6 were evaluated on the basis of values of u_m^+ calculated from Eq. 11 with $\left(\overline{u'v'}\right)^{++}$ from Eq. 16.

Suggested homework: Justify the presence of the terms in $(a^+)^{-1}$ and $(a^+)^{-2}$ by substituting u^+ in Eq. 12 and integrating up to $y^+ \cong 12$.

The term representing the effect of roughness in Eqs. 19 and 20 is based on the experimental data and a correlating equation of Colebrook.[20] Also, see Churchill[21] for a rationalization for this term.

A further discussion of some of the terms and coefficients of Eqs. 16 though 19 is provided in the following section.

OTHER GEOMETRIES AND BOUNDARY CONDITIONS

The methodology described above is applicable to all one-dimensional fully developed turbulent flows, but most alternative geometries and conditions introduce complexities not encountered in a round tube.

According to the analogy of MacLeod,[22] expressions for the velocity distribution in fully developed flow, either laminar or turbulent, when expressed in terms of u^+, y^+ and a^+, are directly applicable for flow between identical parallel plates if a^+ is simply replaced by b^+, the half-spacing of the channel.

Exercise: What is the analog of R?

It follows that the various expressions for $\left(\overline{u'v'}\right)^{++}$ are also directly applicable with this substitution, but those for u_m^+ are not, owing to the different area of integration.

Homework exercise: Derive the analogs of Eqs. 12 through 14 and 20.

The analogy of MacLeod appears to be beautifully confirmed by the plot of the centerline and central-plane velocities in Figure 3 from Whan and Rothfus.[23] Although this remarkable relationship may be shown to be exact for laminar flow, it must be considered speculative and possibly only a very good approximation for turbulent flow.

Exercise: Justify the MacLeod analogy for laminar flow.

This analogy has already been applied implicitly in the determination of the coefficient of Eq. 21 from DNS for parallel plates and in the comparisons of the predictions of Eq. 16 with experimental data in Figures 1 and 2.

Integral formulations for the velocity distribution in terms of the equivalent of $\left(\overline{u'v'}\right)^{++}$ are possible for planar induced (Couette) flow between parallel plates, unconfined forced

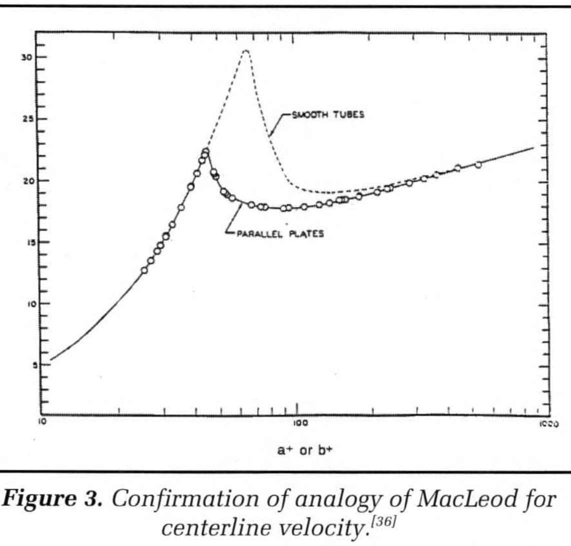


Figure 3. *Confirmation of analogy of MacLeod for centerline velocity.*[36]

flow along a flat plate (even though it is developing and only quasi one-dimensional), forced flow between parallel plates of unequal surface roughness, forced flow through a circular annulus, longitudinal induced (Couette) flow in a circular annulus, rotary induced (Couette) flow in a circular annulus, and combined forced and induced flow between parallel plates and through a circular annulus. Generalized correlating equations equivalent to Eq. 16 have yet to be constructed for any of these flows. Also, except for the first one of these flows, the total shear stress distribution within the fluid is not known *a priori* and must be determined by iterative numerical calculations. This concept fails completely for all two-dimensional channels because of the existence of a secondary motion.

OBSOLETE MODELS AND CORRELATING EQUATIONS

Boussinesq[24] in 1877 proposed perhaps the first quantitative model for a turbulent shear flow, namely

$$\tau = (\mu + \mu_t)\frac{du}{dy} \tag{26}$$

The *eddy viscosity* defined by Eq. 26 has been determined, usually with considerable uncertainty, by differentiating experimental velocity distributions. Generalized correlations of such values have in turn frequently been used to predict velocity distributions and rates of heat and mass transfer. At the same time, this concept has often been scorned by both analysts and practitioners because of its lack of a mechanistic rationale. But re-expressing Eq. 26 in terms of u^+ and y^+, substituting $\tau_w\left[1-\left(y^+/a^+\right)\right]$ for τ and then eliminating du^+/dy^+ between the resulting expression and Eq. 8, reveals that

$$\frac{\mu_t}{\mu} = \frac{\left(\overline{u'v'}\right)^{++}}{1-\left(\overline{u'v'}\right)^{++}} \tag{27}$$

Equation 27 is a remarkable relationship in that it indicates that the eddy viscosity ratio μ_t/μ in a round tube may be interpreted physically as simply the ratio of the rate of transport of momentum by the turbulent fluctuations to that by viscous shear, and is thereby independent of its heuristic diffusional origin. (Boussinesq was either very intuitive or very lucky.) In view of the one-to-one relationship between μ_t/μ and $\left(\overline{u'v'}\right)^{++}$, all of the above exact relationships in terms of the latter may be re-expressed in terms of μ_t/μ with no loss of generality, albeit with some loss of simplicity. Unfortunately, the validity of the eddy viscosity concept is limited to forced flow in round tubes, forced or induced flow between parallel plates of equal roughness, and in confined flow along a flat plate. For all other geometries and conditions, the eddy viscosity is unbounded at some point within the fluid and is negative over a finite adjacent region even though $\left(\overline{u'v'}\right)^{++}$ remains well-behaved. This anomaly occurs because the velocity gradient becomes zero and then changes sign at a different location than does the total shear stress. (See Churchill and Chan[1] for a fuller explanation.)

> *Exercise:* Derive an expression for $\left(\overline{u'v'}\right)^{++}$ at the centerline of a round tube.

Prandtl[25] in 1925 proposed an alternative model for the turbulent shear stress on the basis of a questionable analogy with the kinetic theory of gases, namely

$$\tau = \mu\frac{du}{dy} + \rho\ell^2\left(\frac{du}{dy}\right)^2 \tag{28}$$

where ℓ is a *mixing-length*. Because of its mechanistic basis, and thereby the possibility of predicting the value of ℓ, the mixing-length model has generally been accorded greater prestige among analysts than the eddy-viscosity model. But it is actually inferior in every respect. Re-expressing Eq. 28 in dimensionless form and eliminating du^+/dy^+ between the resulting expression and Eq. 8 leads to

$$\left(\ell^+\right)^2 = \frac{\left(\overline{u'v'}\right)^{++}}{\left(1-\frac{y^+}{a^+}\right)\left[1-\left(\overline{uv}\right)^{++}\right]^2} \tag{29}$$

Equation 29 reveals that the mixing length as well as the eddy viscosity is independent of its heuristic origin and bears a direct relationship to $\left(\overline{u'v'}\right)^{++}$, but it also reveals that the mixing length is unbounded at the centerline of round tubes and at the central plane of a parallel-plate channel where μ_t/μ and $\left(\overline{u'v'}\right)^{++}$ are both finite. In addition, the mixing length is unbounded and negative within the fluid at the same locations in other geometries as the eddy viscosity. How has this false concept survived and found repeated application in the literature of fluid mechanics and heat and mass transfer for over seventy years? Apparently as a result of insufficiently precise experimental data for $\overline{u'v'}$ and u, uncritical or biased processing of these data (see, for example, Lynn[26] and Churchill[27]), and the acceptance of moderate inaccuracy in the resulting predictions of u^+, f, and Nu by practitioners.

Most other models for the prediction of turbulent transport are similarly unsound. For example, the $\kappa-\varepsilon$ models, which function by predicting the eddy viscosity or the mixing length, necessarily share their failures and in addition incorporate considerable empiricism. The LES (large eddy simulation) models and the turbulent shear stress models have promise, but their current implementations necessarily incorporate empirical terms for the region near the wall that may in turn introduce inaccuracy or shortcomings similar to those of the eddy viscosity model. The DNS models alone appear to be free of these sources of error and/or failure, but in their current state of development, they are limited in numerical application to the lowest range of fully developed turbulent flow in very simple geometries. Some aspects of this assessment may be expected to become dated due to new developments in modeling and computation.

Finally, the origins, credentials, and shortcomings of several of the empirical correlations in the literature should be mentioned. The most commonly used correlating equation for the velocity distribution in smooth tubes consists of the first two terms on the right-hand side of Eq. 24, namely

$$u^+ = A + B\ell n\{y^+\} \tag{30}$$

This expression is often cited as a major contribution of mixing-length theory in that it was first derived in 1931 by Prandtl (see Nikuradse[28]) on the basis of the postulate of Von Kármán[29] that

$$\ell = y / B \tag{31}$$

and the idealizations that y/a is negligibly small relative to unity, and that the viscous stress is negligibly small relative to the contribution due to turbulence. But Eq. 30 was subsequently derived by Millikan[30] on the basis of dimensionless considerations alone. He merely postulated a region of overlap between the "law of the wall," $u^+ = f\{y^+\}$, which follows from the postulate of a negligible dependence on a^+, and the "law of the center," which follows from the postulate of a negligible dependence of $u_c^+ - u^+$ on the viscosity.

Exercise: Carry out the details of this derivation.

Nikuradse determined values of A=5.5 and B=2.5 from his experimental measurements. The resulting expression fails for $y^+ < 30$ and for $y^+ > 0.1a^+$ as would be expected from its derivation. Equation 30 may be considered to be displaced by Eq. 17 (with Eqs. 18 and 19), which applies for all y^+ and is presumably more accurate even for intermediate values of y^+ for large a^+ because of the improved accuracy of the data of Zagarola[7] relative to that of Nikuradse.[28] Equations 16, 19, and 20 are inaccurate for $a^+ < 300$ because the exponential and logarithmic terms that arise from Eq. 30 are inapplicable due to the coincidence of its indicated upper and lower bounds at that value.

Integration of Eq. 30 over the cross-section gives

$$u_m^+ = A - \frac{3}{2}B + B\ell n\{a^+\} \tag{32}$$

This expression with separate empirical coefficients rather than 1.75=5.5-(3/2)(2.5) and 2.5 has been widely used for correlation of experimental values of $(2/f)^{1/2}$, and , together with the correlating equation of Colebrook[20] for rough pipe, is the source of the various plots in the literature for the friction factor. These plots may all now be considered to be displaced by Eq. 20 in terms of both convenience and accuracy. A whole literature exists concerning the approximation of expressions such as Eqs. 30 and 32 by one explicit in Re rather than $a^+ = Re(f/2)^{1/2}$, but iterative solution of the original expressions for a specified value of Re is a trivial task even with a hand-held calculator.

One other approach to correlation is worth mentioning because of a recent attempt at resuscitation. Blasius[31] in 1913 correlated the then-available data for the friction factor, which only extended to $Re=10^5$, with the purely empirical expression

$$f = \frac{0.0791}{Re^{1/4}} \tag{33}$$

Prandtl[32] recognized that Eq. 33 implies

$$u^+ = 8.562\left(y^+\right)^{1/7} \tag{34}$$

Nikuradse[33] found that Eq. 34 closely agreed with his own experimental data for smooth pipe and $Re < 10^5$, but that different coefficients and exponents were required for $Re > 10^5$ and roughened pipe. Nunner[34] subsequently found that such values could be represented by

$$u^+ = \beta\left(y^+\right)^{1/\alpha} \tag{35}$$

where

$$\alpha \cong \frac{1}{2/f^{1/2}} \tag{36}$$

and

$$\beta = \frac{(1+\alpha)(1+2\alpha)u_m^+}{2\alpha^2\left(a^+\right)^{1/\alpha}} \cong \frac{\left(1+f^{1/2}\right)\left(1+2f^{1/2}\right)}{\left(a^+\right)^{2f^{1/2}}}\left(\frac{2}{f}\right)^{1/2} \tag{37}$$

Barenblatt[35] has very recently proposed alternative semitheoretical expressions for α and β, but his representation is inferior numerically to that of Nunner for smooth pipe and does not encompass roughened pipe. In any event, Eq. 35 fails totally near the wall where it predicts a negative unbounded velocity gradient and near the centerline where it predicts a finite velocity gradient.

Bird, *et al.*,[9, p.175] noted that expressions for the turbulent shear stress as a function of distance from the wall, such as Eq. 16, lead to simpler integrations for the velocity distribution and the mixed-mean velocity than do expressions in terms of the velocity gradient, such as those involving the eddy viscosity or the mixing length. But in applying this concept, they used an erroneous boundary condition and a purely empirical expression of Pai[36] that does not conform to the known asymptotic behavior and thereby leads to final expressions that are in error both functionally and numerically.

SUMMARY AND CONCLUSIONS

Simple but exact integral expressions are formulated herein for the velocity distribution and the mixed-mean velocity, and thereby the friction factor for fully developed flow in a smooth round tube in terms of a particular dimensionless turbulent shear stress, namely the local fraction of the shear stress due to turbulence. The proposed correlating equation for this latter quantity is not exact, but it has a theoretically based structure and the small error in its predictions is reduced by the numerical integrations used to evaluate the local and mixed-mean velocity. The new, theoretically based correlating equations presented herein for these latter two quantities are presumed, on the basis of comparisons with recent, improved experimental data, to be more exact than any other expressions or graphs in the literature. These formulations are readily extended to other one-dimensional flows.

The eddy viscosity, mixing-length, and $\kappa - \varepsilon$ models are shown to be inapplicable or inferior in every respect to the direct use of correlating equations for the turbulent shear stress itself. Nonetheless, they may produce numerical results of fair accuracy even in applications where they are not strictly valid. The utility of the shear-stress and LES models is currently handicapped by the necessity of incorporating heuristic differential terms for the region near the surface. The DNS models are free of this shortcoming, but their use is limited to simple geometries and a narrow range of flow just above the minimum for fully developed turbulence. All of these models share the inapplicability of the expressions herein for two-dimensional flows such as that in a square duct or an open channel due to the ubiquitous secondary motion.

The material presented herein can be used by teachers of both undergraduate and graduate classes in fluid mechanics and transport as a supplement or replacement for the obsolete section on turbulent flow in all current books.

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ChE *classroom*

TEACHING CREATIVE PROBLEM-SOLVING SKILLS IN ENGINEERING DESIGN

J.G. MACKENZIE, R.M. ALLEN,* W.B. EARL, I.A. GILMOUR
University of Canterbury • Christchurch, New Zealand

Problem solving is an activity that engineers are engaged in every day, but not many professional engineers are taught problem-solving strategies as part of their undergraduate education. In the literature, some writers[1-3] have been particularly concerned with problems based on mathematics and logic, whereas others[4-8] have been more concerned with open-ended problems and lateral thinking.

Some research on problem solving has been based on computer-aided modeling of mental processes known as artificial intelligence (AI).[9-11] Other work has been based on problem-solving experiments with human subjects[12] and studies of thinking.[13] Much of the research, however, has been concerned with logical confusion and errors; little research to date has been done on the teaching of problem-solving skills in higher education.

The teaching of problem-solving skills to undergraduate engineering students has been described.[14-17] From an industrial point of view,[18] problem solving is a crucial skill for engineers in manufacturing. The time to teach this skill is critical in the professional development of an engineer and may be best immediately following graduation when the engineer is confronted with what seems to be an unsolvable problem.

Our view is that there is a balance between teaching problem-solving skills early in the undergraduate degree course so the skills can be used in the educational process, and teaching these skills later when students have the maturity to appreciate their benefits and the experience to apply the techniques. We have chosen to present problem-solving techniques in the third year of a four-year degree program.

A NEW APPROACH TO ENGINEERING DESIGN

In traditional design teaching, the design process is often broken into a number of incremental steps: defining the task, goal setting, establishing a concept, defining the constraints, setting the specifications, listing the alternatives, evaluating and selecting the best alternatives, formulating an appropriate mathematical model, calculating, modifying, costing, drawing, constructing, testing, and finally, commissioning. A general structure of the design process, once recognized and defined, is then adapted as a design strategy for future projects. While the approach of retrospectively studying successful design projects, recognizing the various areas of activities and their logical sequence, and applying it to new projects works well, it relies heavily on experience for a successful outcome. It is exactly this experience in application, however, that our undergraduate students lack. A practical design strategy is more appropriate for novice engineers.

Design has been taught to our chemical engineering undergraduates for many years by a traditional case-studies approach that involved dissecting the design process into its various elements, imparting relevant knowledge by formal

Judith Mackenzie *is Senior Tutor in the School of Engineering, University of Canterbury. She has a Master's degree in Education and has recently completed a PhD in Chemical and Process Engineering. Her teaching and research focuses on the application of computers as a tool for innovative teaching in chemical engineering education.*
Maurice Allen *is Associate Professor in the Department of Instrumentation and Control Engineering at Murdoch University. His teaching and research centers on process control, the modeling and simulation of industrial processes, and the application of computing to process engineering and teaching.*
Brian Earl *is Associate Professor of Chemical and Process Engineering, University of Canterbury. His teaching interests are in process design, corrosion, and electrochemical engineering, and his research interests are in expert systems in process design, chemical engineering education, corrosion, and alternative transport fuels. Dr. Earl is currently on leave at Cornell University*
Ian Gilmour *is Senior Lecturer in the Department of Chemical and Process Engineering, University of Canterbury. His teaching interests are the design of process equipment, heat exchangers, combustion of fuels and energy, and material balances for chemical processes. His research interests are the efficient uses of fuels and energy in the process industry, extraction of nutraceuticals from agricultural and forest residuals, and computer modeling for the pulp and paper industry.*

* *Address: Instrumentation and Control Engineering, Murdoch University, Western Australia 6168*

lectures, and demonstrating how experienced engineers have designed successful systems. It was hoped that this approach would imbue the students with sufficient knowledge and skills to become novice designers.

These efforts to teach design led to the realization that competence in design seemed to be achieved by a handful of students who rose to the challenge and were able to apply skills, knowledge, and other personal attributes, often with outstanding results. The recipe for success seemed to combine such ingredients as organization, lateral thinking, computation, practical experience in workshop skills, and an ability to think in abstract terms. These special talents, which every student possesses, need to be developed and honed to a sharper edge.

. . . there is a balance between teaching problem-solving skills early in the undergraduate degree course so the skills can be used in the educational process, and teaching these skills later when students have the maturity to appreciate their benefits.

In recent years, we have adopted a problem-solving approach similar to that of Woods[19] for teaching third-year engineering design. This design course embraces a wide spectrum of engineering topics: mixing and pumping of liquids, flowsheeting, column design, pinch technology, process reliability, separation processes, and properties of engineering materials. A problem-solving foundation to engineering design provides students with the necessary skills and confidence to be able to tackle any problem, design or otherwise, without feeling hindered by lack of direct experience in the particular topic.

CREATIVE PROBLEM-SOLVING MODULES

Students learn best when they directly experiment with subject matter and are actively involved with the material.[20] Interactive computer instruction provides such active learning and allows students to "review and demonstrate mastery of the material at his/her own pace, [and] provides them with immediate feedback to their responses."[21]

Interactive computer-based learning depends on software that is easy to use, maintains a focus on the concepts, has minimal tediousness, promotes learning, and gives individual guidance. *Strategies for Creative Problem Solving*[15] is a collection of interactive computer modules and is used to supplement problem-solving lectures. Additional features in some modules, such as the use of graphical animation and entertaining motivators, were included to increase student interest in, and motivation for, the module content.[22]

The content of each module is

1. An Introduction to Problem Solving

This module provides the user with the motivation to use creative problem-solving strategies. Topics include the characteristics of effective problem solvers, fear of failure, the need for risk-taking, paradigm shifts, having a vision, a problem-solving heuristic, creative thinking, and working in teams. The introduction presents the topics as well as their application to a contamination problem in a municipal water-supply system.

2. Problem Statement Definition Techniques

The goal of this module is to help the user properly define the problem. Several techniques are used to better define the problem statement: for example, the Dunker Diagram,[19] the McMaster Five-Point Strategy,[19] the Present-State Desired-State technique,[23] and the Statement-Restatement technique. The user reviews the methods of problem definition in two examples: problems at a flashlight manufacturing plant are analyzed with the McMaster Five-Point Strategy and a second example involves a grocery store freezer door fogging up and blocking the customer's view of the contents.

3. Brainstorming: Methods of Solution Generation

This module helps the user generate original yet applicable solutions to a specific problem through brainstorming. The review section introduces the basic techniques and ideas for improvement, including Osborn's checklist,[24] random-word stimulation, futuring, conceptual blockbusting, and using other people's views.

These methods are illustrated through specific examples. To test the techniques, the user is first asked to brainstorm a list of synonyms for the word "money." Once the user is finished, the user's list is compared to one generated by a group of college students. Second, the user selects at least two brainstorming topics chosen from a list of five possible scenarios, ranging from encouraging recycling in a community to preventing zebra mussel infestations on power-plant water-intake pipes. For each scenario, a detailed problem statement is given as well as a few example solutions to get the user started.

4. Potential-Problem Analysis: Avoiding Future Problems

Potential problems should be anticipated and analyzed before they happen. Three parts of potential problem analysis (possible causes, preventative action, contingent actions) are explained in the introduction. The user then has a choice of scenarios (either a cross-country road trip or preparation for an interview) that are used to review the techniques. The main scenario is based on the 1993 world solar-car race, Sunrayce'93.[25] The background of the race is presented with additional explanation of relevant technology, including the solar-cell mechanism and the importance of gear ratios in power-train design. A potential-problem analysis chart for the event is prepared by the user to determine problems that might occur during a race and their prevention.

5. Planning: Implementation of Solutions

Gantt charts,[26] critical-path analysis,[27] deployment charts, and budget proposals are introduced as tools that aid planning. These four techniques are illustrated in two introductory scenarios: planning the ergonomic design of an office and planning a student conference. In the interactive section of the module, the user is part of a team participating in a student competition to build a one-tenth-scale model of a steel bridge. Each of the planning techniques is then applied to generate a Gantt chart, a critical-path chart, a deployment chart, and a budget for the project.

6. Evaluation: Solution Evaluation Techniques

The importance of continually re-evaluating a solution throughout the course of a project is emphasized. The technique presented is the evaluation checklist, illustrated by the near disaster of marketing the new Coca Cola. The example demonstrates the use of an evaluation checklist to prevent millions of dollars from being wasted. In the interactive scenario, the user is presented with the problem of a paper mill that plans to expand its production capacity. The user is given the opportunity to talk to other virtual employees in the company and to gather the necessary information to evaluate the proposed expansion. Findings are submitted to the project supervisor for immediate feedback.

COURSE ORGANIZATION, ASSESSMENT, AND EVALUATION

The problem-solving section of the design course consisted of nine one-hour lectures, six hours of laboratory sessions (with about the same amount of time devoted to working through set problems), and the computer problem-solving modules. This allocation of time was just sufficient to introduce the forty third-year students to the basic concepts, give them the experience of applying these new skills, and expand their confidence in analyzing and solving new problems independently.

We emphasized the importance of communication and working in teams in the process of problem solving. We also used the technique of attacking problems,[28] with one of a pair playing the role of problem solver and the other the listener, and then alternating roles. The first problem-solving assignment, worth 10%, gave randomly selected student pairs the opportunity to apply this technique to a set of problems taken from the McMaster problem-solving program.[19] The second assignment was based on the Fogler interactive computer modules and was also worth 10%. Each pair of students was assigned two of the computer modules to complete each week for three weeks—six modules in total. At the completion of each module, a computer-generated performance score was recorded by students and handed in as part of their assessment. Students were given the option of repeating the modules as often as they wished to improve their score—and some did, with their best score being credited. A questionnaire completed by students at the end of the design course provided an evaluation of Whimbey pairs[28] and the computer problem-solving modules.

RESULTS AND DISCUSSION

The distribution of marks in the first assignment was high, with a skew toward a possible score of ten. When working through the

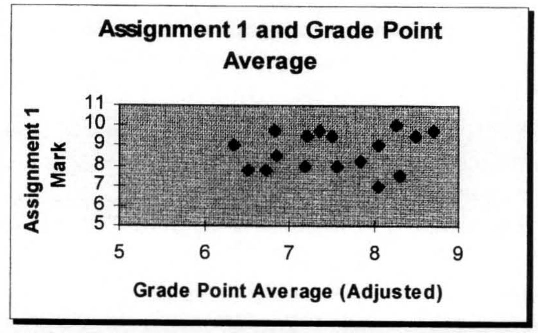


Figure 1. Marks on Assignment 1 compared with adjusted grade point average.

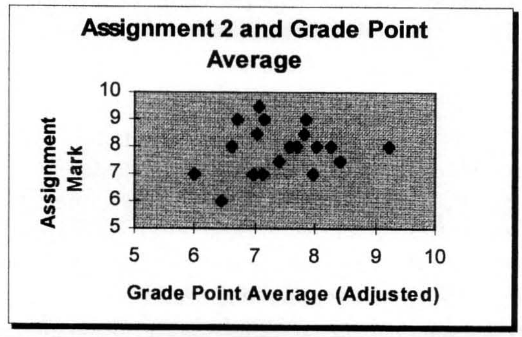


Figure 2. Marks on Assignment 2 compared with adjusted grade point average.

TABLE 1
Student Comments on Whimbey's Method

Problem Solver
- As the problem solver, I found that when solving problems, I tend to like to put things into mathematical equations.
- For the basic problem, I did write out more than I usually would. It was fun and I would like to do more of it.
- I think I work too much out in my head and tend to rush to give an answer.
- I tend to attack problems head on, noting down all the information supplied as I read it through.
- I enjoyed solving these problems.
- The help of a listener was very useful; their ideas and reasoning are often very different and it's good to compare and see their point of view.

Listener
- In problem solving you must read the question carefully, jot down any conditions, and then determine what the problem is asking you to solve.
- The hardest thing was not to get carried away and tell the problem solver the answer when I knew it.
- It was a much easier task to be the listener than the solver.
- It's good to try to show the other person a different way of thinking.
- Being the listener is not an easy task!
- Listening is generally not too hard—often the solver doesn't vocalize everything.

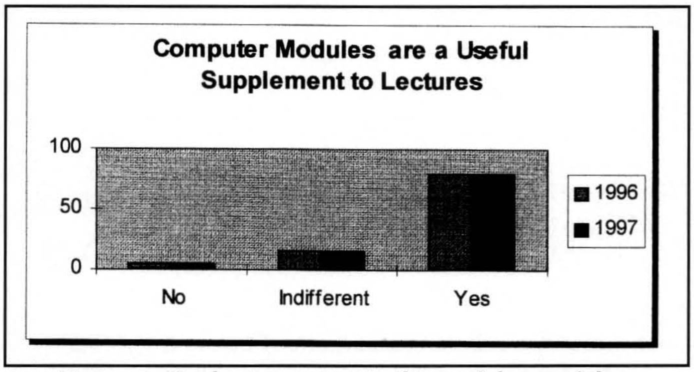


Figure 3. Student response to the usefulness of the interactive computer modules.

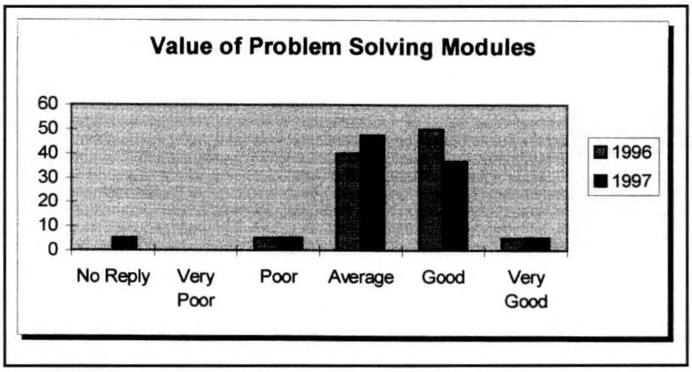


Figure 4. Students opinion of the value of the interactive problem-solving modules.

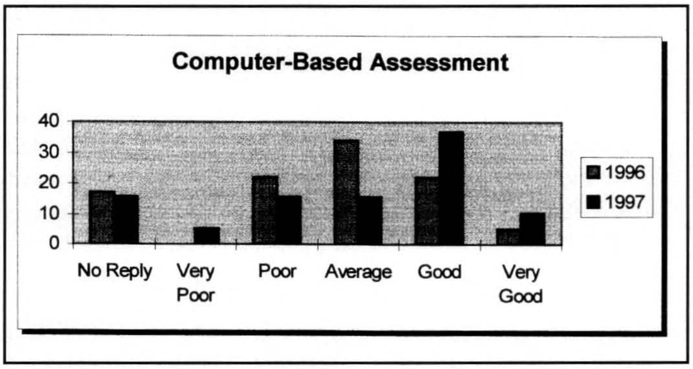


Figure 5. Student response to computer-based assessment.

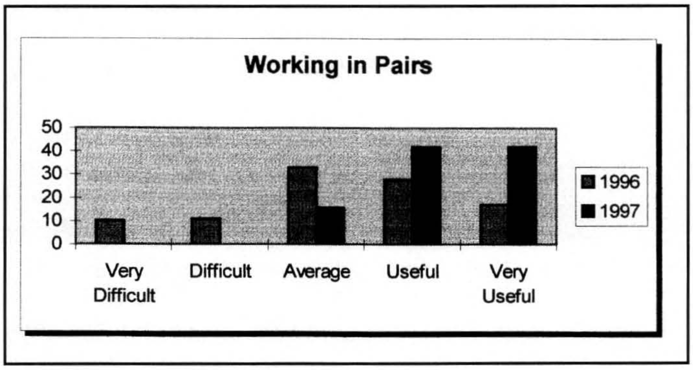


Figure 6. Student response to working in pairs.

McMaster problem set, a number of students showed enthusiasm for the Whimbey pair concept, obtaining full marks. Table 1 has a sample of student comments taken from the questionnaire.

The assessment mark for each pair for two problem-solving assignments has been compared with the group-adjusted grade point average for the 1996 end-of-year examinations in Figures 1 and 2.

The grade point average (GPA) for each student is the average grade for all papers in the 1996 examinations and reflects the students' final academic achievement. The GPA is assigned a numerical equivalent ranging from 9 for an A+ to 2 for a C. The adjusted grade point average (GPAJ) was recalculated to align means and standard deviation with marks out of 10.

Statistical analysis showed no significant relationship between problem-solving performance and previous academic results for the two problem-solving assignments. A reason for the results is that problem solving is a different skill from conventional academic performance. Additionally, the results can be explained by differences in testing procedures. The problem-solving assignments were power assessments, without direct time constraints, whereas examinations were speed tests, with stringent time restrictions to the examination time.

Student responses to the questionnaire on the usefulness of the computer modules, their rating of the interactive problem solving modules, their opinion of computer-based assessment and working in pairs are shown in Figures 3 through 6.

Figure 3 shows that 78% of students in 1996 and 1997 found the computer modules to be a useful supplement to lectures, while 10% were indifferent and 2% did not find them useful.

In Figure 4, student rating of the interactive problem-solving modules indicated a positive response, with fewer than 5% (1996) and fewer than 10% (1997) rating them as worse than average. Students responded well to the practical problems in the computer modules, helping to understand different problem-solving techniques.

Computer-based assessment was introduced to the students in 1996. Figure 5 shows that 61% (1996) and 63% (1997) of the students found this form of assessment very good, good, or average; 17% of the students (1996) did not respond to this question.

The interactive computer modules provided a new and different environment for learning that students found to be a useful supplement to lectures. Working in pairs for Assignments 1 and 2 enabled students to help each other with problem solving. Most of the students supported working in pairs for Assignment 2, as shown in Figure 6; 78% of the

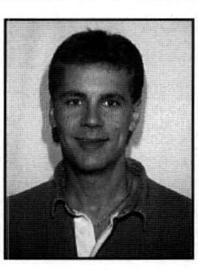
Continued on page 157.

The object of this column is to enhance our readers' collections 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 and that elucidate difficult concepts. Manuscripts should not exceed ten double-spaced pages if possible and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

ICING THE RINK
A Problem for the Stoichiometry Course

David A. Dudek
North Carolina State University • Raleigh, NC 27695-7905

During the fall 1997 semester at N.C. State University, I was both captain of the ice hockey club and the head teaching assistant for the problem session of the stoichiometry course. It occurred to me that the process used to freeze an ice rink illustrates several stoichiometry course topics, so I constructed an exercise that called for the students to go to a home hockey game, observe the ice resurfacing operation, and estimate the power rating of the rink compressor. I believe the exercise served a number of useful functions, including reinforcing the students' understanding of several thermodynamic principles and methods, showing them that those principles and methods have real-world relevance, and introducing many of them (notably, those born and raised in the South) to the fun and excitement of ice hockey. The fact that it increased attendance at our home games didn't hurt either.



David Dudek earned a BS in Chemical Engineering and a BA in Economics in 1993 from the University of Illinois. He received an MS in Management in 1997 and a PhD in Chemical Engineering in 1998 from NC State University. He completed his PhD in chemical engineering in 1998. His dissertation research concerns modeling and experimental aspects of copper electrodeposition from cuprous cyanide electrolyte. He also has nineteen years of ice hockey experience.

About a month before the end of the semester I handed out an outline of the ice resurfacing process and a series of problems to be solved. I told the students that if they attended a game and made a reasonable effort to solve the problems, they could replace their lowest problem-session grade with a 100 (if their estimated compressor rating was within a factor of three of the actual rating) or an 80 (if their estimate was outside that range). Although I required game attendance to receive credit on the problem, attendance is not necessary to complete the problem presented here.

This paper presents the process description and problem statement, outlines the problem solutions, and summarizes the students' performance on the exercise.

PROCESS DESCRIPTION

The process used to freeze an ice rink is shown schematically in Figure 1. At the lower left of the figure, saturated Freon (R-22) vapor (low T, low P) enters a compressor in which its pressure is raised. Essentially all of the shaft work transmitted to the gas in the compressor is converted to internal energy and the gas temperature and pressure accordingly increase. The Freon gas leaving the compressor (high T, high P) comes into thermal contact with much cooler air in a heat exchanger (the condenser) and is completely condensed. The saturated liquid Freon (low T, high P) goes through an adiabatic expansion valve in which its pressure drops substantially.

At the lower pressure, the Freon is above its boiling point and some of it vaporizes, which in turn leads to a dramatic drop in the Freon outlet temperature. (Consider: When you are wet and water evaporates from your body, you get cold.) The liquid/gas mixture (low T, low P) enters a second heat exchanger (the boiler) where it comes into thermal contact with cool liquid propylene glycol (a liquid with a high boiling point similar to ethylene glycol, the coolant used in automobile radiators). Heat is transferred from the cold propylene glycol to the much colder Freon, chilling the glycol and vaporizing the remaining Freon liquid. The Freon gas (low T, low P) then circulates back to the compressor to begin another cycle. The cold propylene glycol passes through coils under the ice. Heat flows from the ice to the glycol, causing any liquid water on the ice to freeze and warming the glycol, which circulates back to the boiler to be chilled again.

The rink freezing process has two distinct periods: one when liquid water placed on the rink is frozen and the power load on the compressor is high, and the other when the ice is simply being kept from melting and the power load is low. The required compressor power rating (size) is based on the load during the first of these periods.

It occurred to me that the process used to freeze an ice rink illustrates several stoichiometry course topics, so I constructed an exercise that called for the students to go to a home hockey game, observe the ice resurfacing operation, and estimate the power rating of the rink compressor.

PROBLEMS

(a) You have just seen that a major component of a process to freeze water is a compression that heats a gas to a temperature well above 0°C. Most people would find heating a gas in order to freeze a liquid strange. Explain in your own words how the work done by the compressor eventually leads to freezing the rink.

(b) Consider the Freon and propylene glycol collectively as a system. Where in the process is energy added to the system and where is energy transferred from the system? (Neglect heat losses from the lines connecting the different process units.) Assuming that the system operates at steady state, write an expression relating the various energy inputs and outputs.

(c) The purpose of resurfacing the ice is to turn rough, snow-covered ice into a smooth flat surface. To do this effectively, the Zamboni (http://www.zamboni.com/) collects the snow, shaves a thin layer of ice from the surface, and uses hot water to melt the remaining grooves and leave a smooth wet surface. Thus, the Zamboni is filled with water from the

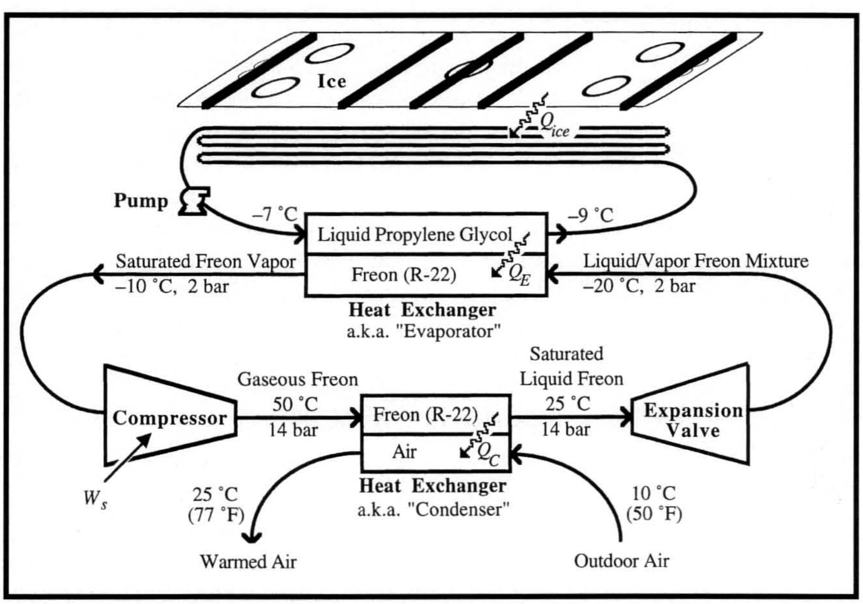


Figure 1. *Cooling system for a typical ice rink.*

hot water tap at the rink. At most rinks, this water is warmer than the water in the average household water heater. Estimate the temperature (°C) of the water coming out of the Zamboni.

(d) Make a reasonable guess at the temperature (°C) of the ice on the frozen rink.

(e) How much energy (kJ/mol) must be transferred to

(i) Cool water from the temperature you estimated in Part (c) to its freezing point

(ii) Freeze water at 1 atm

(iii) Cool ice from the freezing point to the temperature estimated in Part (d).

(f) How much energy (kJ/mol) must be transferred to convert water from the Zamboni to ice at the rink temperature? If your temperature estimates in Parts (c) and (d) are each incorrect by 10°C, what is the maximum percentage error in your calculated energy? Why is the error so small?

(g) If the Zamboni puts 200 gallons of hot water on the ice and it takes 15 minutes for the entire surface to freeze, at what rate (kJ/h) must heat be transferred to the cooling coils under the rink?

(h) Compressors are often rated in tons of refrigeration, where one ton is equivalent to 12,000 BTU/h. Generally speaking, the required compressor shaft work is about 30% of the heat load from the ice, and compressors at ice rinks are about 40% mechanically efficient (meaning that 40% of the total power generated by the compressor is delivered as shaft work to the process fluid). Using these rules of thumb, estimate the rating of the compressor in tons of refrigeration.

(i) Apply the energy balance derived in Part (b) to estimate $-Q_c$, the rate at which energy is removed from the system by the compressor.

PROBLEM SOLUTIONS

(a) Compressing the gaseous Freon increases its pressure and temperature. At the higher pressure, the boiling point of the Freon is well above room temperature. Thus, a large amount of energy can be removed from the Freon by condensing it with room-temperature air. When the Freon passes through the expansion valve, its pressure returns to the pre-compression pressure, but its temperature falls well below the pre-compression temperature. At the lower pressure, the boiling point of Freon is below the freezing point of ice. Thus, a large amount of energy can be removed from the coolant under the ice by boiling the low-pressure Freon.

(b) Energy is added to the system by the ice (Q_{ice}) and by the compressor (W_s). Energy is removed from the system by the condenser (Q_c). Thus, the energy balance is $Q_{ice} + W_s + Q_c = 0$.

(c) 120 to 160°F, or 50 to 70°C

(d) 18 to 24°F, or -4 to -8°C

(e) $C_{p,water}$ = 75.4 J/mol °C; $\Delta H_{melting}$= 6,009 J/mol; and $C_{p,ice}$ = 36.7 J/mol °C.

Thus

(i) 75.4 J/mol °C x (0-60) °C = - 4,524 J/mol

(ii) -6,009 J/mol

(iii) 36.7 J/mol °C x (-6-0) °C = -220 J/mol

(f) -4,524 J/mol + -6,009 J/mol + -220 J/mol = - 10,753 J/mol.

If both temperature estimates are off by 10°C, the error is only about 10%. This number is so small because a large portion of the energy requirement in Part (e) is the latent heat of freezing.

(g) 200 gal x (1 m^3/264.17 gal) x 1000 kg/m^3 = 757 kg

10,753 kJ/mol x 757 kg x (1 kmol/18 kg) ÷ 0.25 hr = 1.81 x 10^6 kJ/hr

(h) 1.81 x 10^6 kJ/hr x 1000 J/kJ x 9.486 x 10^{-4} BTU/J x (1 ton/12,000 BTU/hr) = 143 ton

0.3 x 143 ton ÷ 0.4 = 107 ton

(i) $-Q_c = Q_{ice} + W_s$

$-Q_c$ = 143 + 107 = 250 ton

STUDENT OUTCOMES

Of 144 students taking the course, 43 (30%) elected to do the problem. Of the 43, roughly one-third did the calculations correctly and came within a factor of three of the actual compressor rating of 130 tons, one-third made poor estimates of intermediate quantities and estimated ratings outside the allowed range despite doing the calculations correctly, and the remaining one-third did the calculations incorrectly. The problem given to my students required estimation of the volume of hot water placed on the ice; because this was the most difficult number to estimate accurately, the number (200 gallons) is provided in the above problem statement. Common mistakes included using the heat capacity of water vapor instead of liquid, making mistakes in signs of sensible and latent heats, and unit conversion errors.

ACKNOWLEDGMENTS

I am indebted to Professors Richard Felder for carefully reading the problem and providing numerous useful suggestions and Peter Kilpatrick for helpful discussions regarding the thermodynamics of refrigeration cycles. Thanks also to Randy Lee for an educational tour of the boiler room at The Ice House in Cary, North Carolina, and for providing accurate parameter values. ❐

Problem-Solving Skills

Continued from page 153.

students found it to be very useful, useful, or average. Sharing ideas and discussing them were understood to be valuable problem-solving techniques. The main disadvantage for students was having to plan time to work together. In 1997, student opinion of the problem-solving modules improved significantly, as shown in Figures 3 through 6.

ASSESSMENT OF EACH MODULE

Each module was assessed and marks recorded on-line. Tables 2 and 3 show the mean and standard deviation of student assessment for each computer module. In 1996, all students scored full marks on the introduction module, whereas this module ranked fourth in 1997. Planning and brainstorming ranked the lowest for both 1996 and 1997. We believe that students lack the necessary experience in these skills that are developed later in the workforce.

TABLE 2
Student Assessment of Each Computer Module, 1996

	Mean	Standard Deviation
• Introduction	1.00	0.01
• Potential Problems	0.98	0.06
• Evaluation	0.89	0.17
• Define	0.86	0.15
• Planning	0.68	0.21
• Brainstorming	0.41	0.25

TABLE 3
Student Assessment of Each Computer Module, 1997

	Mean	Standard Deviation
• Define	0.92	0.10
• Evaluation	0.87	0.21
• Potential Problems	0.86	0.09
• Introduction	0.83	0.11
• Brainstorming	0.65	0.27
• Planning	0.64	0.07

CONCLUSION

The development of problem-solving skills is an integrated part of the teaching of design at the third-year level of our chemical and process engineering degree course. Students appreciated the problem-solving approach to assignments. Working in pairs for problem solving was found to be beneficial by most of the students, although arranging a suitable time to work together was a disadvantage.

Problem solving is a skill that can be learned. It is imperative that our graduates have the necessary skills and strategies to deal confidently with new situations and problems encountered in their professional careers.

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EXPERIENCE WITH TEACHING DESIGN

Do We Blend the Old With the New?

LAWRANCE FLACH
University of Dayton • Dayton, OH 45469-0246

One of the most challenging tasks facing a chemical engineering instructor today is presenting a capstone design experience that comprises an appropriate balance between the "old" and the "new." The old would be the classical design experience, heavy on the fundamentals, hand-calculation intensive, and rigorous in approach, whereas the new corresponds to a more team-oriented, computer-usage intensive approach incorporating the development of written and oral communication skills. Based on the proliferation of articles in the literature on the subject of teaching design and how design should be integrated into the curriculum,[1-8] it is obvious that this is an issue that continues to be debated and for which there is no simple solution. There also appears to be some disagreement between industry and academia as to what skills a student should possess after completing a four-year engineering program.[9,10]

This article addresses some of the issues associated with teaching design and in particular looks at the capstone design sequence developed at the University of Dayton and the experience gained developing and teaching these courses. The pros and cons of chemical-process flowsheet-simulator use, together with feedback from students who have taken the design courses, will also be discussed.

DESIGN COURSE SEQUENCE

The design course sequence, as it has evolved over the last seven years, is outlined in Tables 1 and 2. As can be seen, the first course (Design I) is offered during the fall semester of each year and the second course (Design II) during the following semester. Design I is a fairly standard introductory design course covering topics such as the basic concepts of design, safety issues, costing and economic analysis, materials of construction, and some mechanical design. Additional details can be found in the table. Evaluation of student performance for this course is based on two midterm examinations as well as a comprehensive final examination. Performance on homework assignments is also weighted into the final course grade.

Design II, the second course in the sequence, has two main components: the design problem and special topics. The design problem is a fairly comprehensive plant design (discussed later), and the special topics include diagrams and layout, optimization, shortcut design procedures, and other topics specifically related to the design project being undertaken, *e.g.*, if the plant design requires a bioreactor, some details of microbial growth kinetics and fermenter design would be discussed. Evaluation of student performance for this course is based on a single examination (toward the end of the semester) that covers the special topics as well as some aspects of the design problem, and grades from the design-project assignments. The assignment grades would typically constitute approximately two-thirds of the final course grade. Some additional details can be found in Table 2.

DESIGN PROJECTS

As mentioned above, the major component of Design II is a fairly detailed plant design. Details of some of the projects undertaken are available in Table 2. Selection of appropriate projects is important. They need to be feasible, yet challeng-

Lawrance Flach, *Associate Professor of Chemical Engineering at the University of Dayton, has bachelors and masters degrees in chemical engineering from the University of Cape Town, South Africa, and a PhD from the University of Colorado, Boulder. He conducts research in the areas of process modeling, dynamics, and control.*

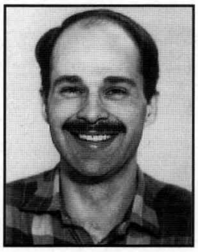

TABLE 1
Design I Course Outline
Fall Semester • 3 Credit Hours

1. *Introduction (0.5 week)*
   - Basic concepts
   - Steps in the design procedure
2. *Safety, Loss Prevention and Health Issues* (2 weeks)
   - MSDS (Material Safety Data Sheet) terminology
   - Health, safety hazards: toxicity, flammability, explosions, etc.
   - Loss prevention, HAZOP studies
3. *Capital Cost Estimation* (2 weeks)
   - Equipment costing, cost charts, cost indices, etc.
   - Overall plant cost, Lang Factor method
4. *Manufacturing Cost Estimation* (1 week)
   - Fixed capital, working capital
   - Direct, indirect, general manufacturing expenses
5. *Economics and Profitability Analysis* (2 weeks)
   - Interest
   - Present value of money
   - Depreciation
   - Profitability analysis, discounted cashflow
   - Break-even analysis
6. *Materials of Construction* (3.5 weeks)
   - Introduction
   - Mechanical properties of materials
   - Phase transformations and heat treatment
   - Corrosion
   - Special properties required of materials
   - Materials selection
   - Commonly used materials of construction
7. *Mechanical Design of Process Equipment* (1 week)
   - Design pressure, temperature, stress
   - Joint efficiency, shells and heads
   - Design equations
   - Vessel supports

TABLE 2
Design II Course Outline
Spring Semester • 3 Credit Hours

1. *Design Problem* (different problem each year) [class size]
   - 1991 Revamp NGL processing unit (based on 1991 AIChE Student Design Contest Problem) [27 students]
   - 1992 Methanol from coal plant [27 students]
   - 1993 MEK from 2-butanol plant [29 students]
   - 1994 Ethanol production from molasses by fermentation [23 students]
   - 1995 Methanol plant (based on 1995 AIChE Student Design Contest Problem) [25 students]
   - 1996 Hydrogen from methane plant [37 students]
   - 1997 Ammonia from natural gas plant [23 students]
2. Special Topics
   - Flowsheeting, P&I diagrams, symbols
   - Short-cut design procedures, "rules-of-thumb"
   - Process optimization
   - Plant layout
   - Computer-aided design programs, ChemCAD III
   - Other topics, as required for the design problem

ing for the students, and preferably should incorporate a variety of basic unit operations and some form of material conversion. Exotic separation techniques or reaction systems are generally avoided due to their complexity, but may be included to illustrate the power and capability of computer simulation packages.

Students are guided through the plant design via a number of assignments that are distributed throughout the semester and are typically 10-14 days duration. Details of a typical assignment sequence can be found in Table 3.

Each assignment is comprehensive and in some cases requires the students to write computer programs to perform the design, *e.g.,* incremental design of a packed-bed catalytic reactor. Some aspects of the mechanical design of vessels are included where appropriate.

A report is submitted upon completion of each assignment, and currently each student is expected to submit a report, *i.e.,* report writing is performed individually. Although some level of collaboration between students does occur while working on these assignments, excessive collaboration is discouraged because overall course grades are individual and to a large extent are based on the assignment reports. Performing these assignments and writing the reports in teams is something that has been considered because of the "teamwork" experience that would be gained by the students and also for the reduced work load in evaluating the assignment reports. To date, however, we have continued to require individual assignment reports, mainly because we view student performance in this course as somewhat of an overall indicator of the student's ability, and as such we have preferred an individual assessment of performance.

USING FLOWSHEET SIMULATORS

Using chemical process flowsheet simulators, such as ChemCAD,[11] has been gradually introduced during Design II over the last five years. Initially, use was limited to certain assignments, and in some cases hand calculations were required prior to using the simulation package. More recently, use of simulation packages has not been limited and students

TABLE 3
Typical Sequence of Design Project Assignments

1. Process background and literature, overall material balance
2. Material and energy balances
3. Reactor design
4. Heat exchanger design
5. Distillation or absorption design
6. Miscellaneous equipment design and preliminary costing
7. Economic analysis, final report

This article addresses some of the issues associated with teaching design and in particular looks at the capstone design sequence developed at the University of Dayton and the experience gained developing and teaching these courses.

have been free to use them as much as they like. This approach, however, has had mixed results. Some students revel in the situation, can use the packages well, and get good results quickly. Others appear to become obsessed with getting a computer simulation to work for a situation where a few hand calculations would be perfectly satisfactory. As a result, a tremendous amount of time and effort is wasted on getting the packages to work rather than learning anything of engineering significance. This is the situation that we had tried to avoid by limiting package use previously.

One cannot question the ability of simulation packages to efficiently and conveniently perform many chemical engineering calculations, but one should never forget that using these packages is sometimes more difficult than doing calculations by hand, and that sometimes the results obtained may just not be realistic or appropriate for the situation being considered. Many students tend to present results obtained from a simulation without really considering their applicability. Sometimes a "back-of-the-envelope" hand calculation or "common sense" can reveal where problems lie. One should thus try to avoid situations where simulation packages are overused and thus become a substitute for a basic understanding of the chemical and physical phenomena occurring.

STUDENT FEEDBACK

Student feedback concerning these two courses has been generally positive. On the university-administered course evaluation, when asked to give the courses overall ratings, Design I received an average of 2.8 and Design II an average of 3.0 for the last six years (4=excellent, 3=above average, 2=average). When asked if they had learned a great deal from the courses, Design I received an average of 3.1 and Design II an average of 3.3 (4=strongly agree, 3=agree, 2=neutral).

On a departmentally administered comment sheet used for Design II, students were asked about the course's strengths, its weaknesses, and suggestions for improving it. As is typical for such a survey, there was a wide variety of responses. The general nature of the student comments was

> <u>Course strengths:</u> *Good capstone course, incorporating many of the skills and techniques learned throughout the curriculum; linked many of the topics studied separately prior to this course.*
>
> <u>Course weaknesses:</u> *Excessive work load and time-consuming; lack of guidance on some assignments.*
>
> <u>Suggestions for improvement:</u> *More guidance and details of what is expected on assignments; reduce workload (possibly by working in teams).*

The workload during Design II is high, and we are addressing the issue by making some curriculum changes that will allow us to distribute more of the workload between Design I and Design II. Workload during Design I is typically a lot lower than that required during Design II, and we believe that the changes that we will introduce in the near future will alleviate this problem and result in a more even distribution of effort. The teamwork issue is one that continues to be debated.

CONCLUDING REMARKS

The senior-year chemical engineering design sequence at the University of Dayton has evolved over the last decade. Some of the "new" innovations (use of process flowsheet simulation packages) have been introduced with some success, but for the most part we have retained a more traditional approach to teaching these courses. This was intentional.

We are living in a time when industry expects students to graduate not only with a good fundamental understanding of chemical engineering principles, but also with the skills traditionally acquired after graduation via industrial or work experience. The latter are skills best acquired in an actual work environment, and as such can be acquired by a student through internship or co-op programs. If a student chooses not to participate in these programs, then prospective employers need to appreciate that the graduate will be lacking that practical experience and associated skills. If the graduate possesses a good understanding of the fundamentals, however, then these experience-based skills can be acquired fairly rapidly in the work environment.

Universities, and engineering programs in particular, are under tremendous pressure to recruit students and then to retain them at all costs. As engineering educators, we must resist the impulse to accomplish these goals by "watering down" the programs. The design sequence described in this paper demonstrates our resistance to the trend and indicates that we are trying to provide our students with a good grasp of the fundamentals. Feedback that we have received from industry-employed graduates indicates that they have benefited from this approach and that they have been more than capable of competing and succeeding in today's work environment.

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This column provides examples of cases in which students have gained knowledge, insight, and experience in the practice of chemical engineering while in an industrial setting. Summer internships and co-op assignments typify such experiences; however, reports of more unusual cases are also welcome. Description of the analytical tools used and the skills developed during the project should be emphasized. These examples should stimulate innovative approaches to bring real world tools and experiences back to campus for integration into the curriculum. Please submit manuscripts to Professor W. J. Koros, Chemical Engineering Department, University of Texas, Austin, Texas 78712.

INTERNATIONALIZING PRACTICAL ChE EDUCATION

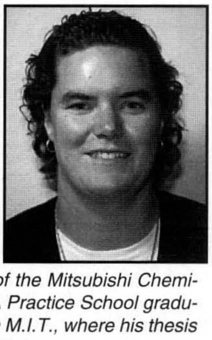
The M.I.T. Practice School in Japan

ANDREA J. O'CONNOR, ANGELO W. KANDAS, YUKIKAZU NATORI, T. ALAN HATTON

Massachusetts Institute of Technology
Cambridge, MA 02139
Mitsubishi Chemical Corporation, 3-10 Ushiodori
Kurashiki • Okayama 712, Japan

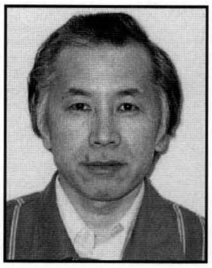
Graduates entering today's increasingly global chemical industry require not only strong technical skills, but also the ability to apply those skills successfully to solve practical problems along with an appreciation of the diverse features of industry around the world. Although classroom education is not the optimal way to develop all of these skills, it can be well complemented by practical experience gained outside the traditional university environment. Many internship and cooperative education programs exist to provide students with industrial experience during their undergraduate and graduate engineering courses, but exposure to the international world of industry and business is generally not available to students until after they commence graduate employment.

Recognizing the importance of developing an understanding of international industrial practices in its graduates, the David H. Koch School of Chemical Engineering Practice (the "Practice School") opened a new chapter in its history two years ago by initiating its inaugural overseas station. The Practice School, administered by the Department of Chemical Engineering at M.I.T., has educated chemical engineers in both the science of chemical engineering and the art of chemical engineering practice since 1916, with only



Andrea J. O'Connor *was the Station Director of the Mitsubishi Chemical Corporation Station in the summer of 1997 and the Molten Metal Technology Station in the summer of 1996. She holds a PhD in chemical engineering from the University of Melbourne and was a Fulbright Postdoctoral Fellow at M.I.T. in 1995-96. She is now a lecturer at the University of Melbourne and conducts research in separation processes and surfactant systems.*

Angelo W. Kandas *was the Assistant Director of the Mitsubishi Chemical Corporation Station in the summer of 1997. A Practice School graduate, he holds a PhD in chemical engineering from M.I.T., where his thesis was on "The Evolution of Carbon Structure During Oxidation." He is now a Senior Process Engineer at Intel Corporation, conducting research on oxide etching. (Photo not available.)*



Yukikazu Natori *is Deputy Director of the Development and Engineering Research Center at the Mitsubishi Chemical Corporation's Mizushima Plant. He joined Mitsubishi Chemical Corporation after graduating from Tokyo Institute of Technology with a Master of Science in chemistry and has diverse experience in the development and design of petrochemical plants at the Mizushima Plant.*

T. Alan Hatton *is the Ralph Landau Professor of Chemical Engineering Practice and has been Director of the Practice School program since 1989. A native of South Africa, he graduated from the University of Wisconsin, Madison, with a PhD in chemical engineering and has research interests in novel separation processes and interfacial phenomena.*

brief interruptions during the two World Wars.[1] The Mitsubishi Chemical Corporation (M.C.C.) Mizushima Plant in Kurashiki, Japan, was selected as the site of the program's first industrial station outside the U.S., and it hosted seven M.I.T. student for two months in the summer of 1997.

The key issue in establishing an overseas Practice School station was to ensure that the quality of the educational experiences gained by the students was not diminished by the cultural or language differences, but rather was enhanced by exposure to these differences. With careful preparation by M.I.T. and M.C.C. staff and strong support of the students' endeavors at the station, the station operated very successfully. This article describes how the station was established and the benefits and difficulties of the addition of an overseas station to the Practice School program.

THE PRACTICE SCHOOL

Students enrolled in the Practice School undertake two semesters of graduate-level courses in chemical engineering at M.I.T., followed by three to four months of intensive project work at two remote industrial stations. Successful completion of these tasks leads to graduation with a Master of Science in Chemical Engineering Practice. The industrial project work takes the place of the thesis component of some other Masters programs, and a high standard of achievement is therefore expected. Industrial stations have operated at a number of different company sites—recently Dow Chemical (Freeport, Texas), Merck Pharmaceutical (West Point, Pennsylvania), GE Plastics (Mt. Vernon, Indiana), and Cargill (Minnespolis, Minnesota) have hosted Practice School groups.

The students work in groups of two or three, and each group works on one project for four weeks. In this short time, the students must assimilate the problem they are assigned, develop a method of approach, carry out the project work, and present both written and oral reports. Their efforts are supervised and assessed by the Station Director and the Assistant Station Director, both M.I.T. staff members who reside at the station full-time. The program is structured with regular meetings and reporting deadlines to ensure the students' efforts are appropriately focused and that good communication is maintained between the students, the project sponsors, and the Station Directors for the duration of the project. Details of the program structure have been described previously.[2]

One student from each project group is designated as the group leader and is responsible for management of the project and effective communication throughout the course of the project. All students contribute to oral and written reports each month, and the groups and group leaders are changed for each new project. Company engineers act as project sponsors, providing problems for the students to work on and acting as consultants to the student groups. The M.I.T. staff and students are bound by confidentiality agreements with the host companies, so they are granted broad access to in-house data and know-how.

The projects must meet a number of criteria in order to be suitable for the Practice School: they must be of educational value to the students; they must require in-depth technical work, original thinking, initiative, and engineering judgment in their execution; and they must be of high priority to the host company. Furthermore, the personnel, plant, and other resources necessary for the project to progress must all be available during the four-week period that the project is assigned to the students. Routine delays such as those required to purchase a new equipment item cannot be accommodated after projects commence due to their short duration. It has been estimated by plant project engineers at previous stations that, as a result of these students' single-project focus, diligence, and aptitude, a typical pair of Practice School students can achieve in one month of work on a project what a company engineer might require four to six months to complete.

THE M.C.C. STATION

The opportunity to experience from within the day-to-day operations of M.C.C.'s Mizushima Plant was understandably inspiring to the students selected to attend this station. M.C.C. is the largest chemical manufacturer in Japan, and the Mizushima Plant is one of their major operations, with around 1800 employees and $1.1 billion worth of product shipped annually (1995 data). The plant is located in a petrochemical industry complex with port facilities on the Seto Inland Sea, and it manufactures a broad range of petrochemicals and memory media for computers. In

Many internship and cooperative education programs exist to provide students with industrial experience during their undergraduate and graduate engineering courses, but exposure to the international world of industry and business is generally not available to students until after they commence graduate employment.

addition to the manufacturing facilities, the Mizushima Plant has the Development and Engineering Research Center (DERC), which conducts a broad range of process development, modeling, and optimization projects to develop leading-edge technology for the future operations of M.C.C. This center was the host to the Practice School, and projects were offered by several specialist groups within the center, led by M.C.C. engineers with strong technical and English language skills.

Seven students were selected to attend the station based on their expressed interest to work in Japan. They spent one month at the Dow Corning station (Midland, Michigan) prior to arriving at M.C.C., where they worked for two months. It was important for the students to gain experience in a U.S. Practice School station before tackling the program in Japan, to familiarize them with the program expectations and to give them confidence in their ability to meet these expectations in a more familiar environment. The students all held undergraduate engineering degrees and had completed the graduate course requirements of the Practice School program at Cambridge. Only one of the selected students spoke Japanese, so the others also enrolled in an introductory Japanese course at the local Adult Education Center, and all attended two half-day workshops run by the M.I.T. Japan Program to prepare them for living and working in Japan. Visas and work permits were arranged for the students, the only difficulty being the added documentation and guarantees of support required for some non-U.S. students.

The students arrived in Japan several days before commencing work, enabling them to recover from jet lag and acclimatizing them to living in Japan. Apartments were provided in the M.C.C. housing complex alongside Japanese employees and their families. The costs for housing, as well as for travel to and from Japan, were covered by M.C.C. Initial challenges facing the students included learning to manage shopping, banking,

Case Study 1. Optimization of Polymerization Catalyst Properties

A polymerization catalyst is synthesized in a batch process by precipitation from a reaction mixture following a complex sequence of reagent additions and temperature adjustments. Increased demand for certain polymer product grades necessitated improved control of the catalyst particle size distribution (PSD) in order to maximize the production capacity of the polymerization train.

The students initially performed a statistical analysis on the existing laboratory and pilot-plant data for the catalyst synthesis under a range of conditions. Using techniques learned in a Practice School course on statistical analysis and experimental design, they were able to determine which variables have a dominant effect on the catalyst PSD, but did not have sufficient data to quantify these effects. So they used the statistical analysis software SAS to design an experimental program to investigate the effects of the dominant parameters. Appropriate experimental design was important to maximize the information obtained from the limited number of laboratory experiments possible in the short time frame, as each experiment took about fourteen hours to complete.

The students then conducted the experiments in collaboration with their project sponsors. They planned their time carefully so that two students were in the laboratory at all times during an experiment; the third group member was also in the laboratory for the more labor-intensive parts of the experiments, and in the office the rest of the time. This was necessary to enable the group to read sufficient background material, to develop data-analysis techniques, and to meet the weekly reporting deadlines. They arranged a roster to share the duties most efficiently.

On-line measurements of the PSD using a laser-reflectance probe provided extra information from the students' experiments, enabling them to identify further important variables that had not been previously studied. It also enabled them to postulate the mechanisms governing the PSD, providing key insights into the physics of the process. The experimental results were added to the existing data set and analyzed using SAS to determine the dependence of the catalyst PSD on the manipulated variables. The results confirmed the trends previously observed in pilot-plant trials, but also identified some important variables that were previously not considered significant. The students recommended changes to the catalyst synthesis procedure based on their results, and they were implemented with distinct improvements in the catalyst properties.

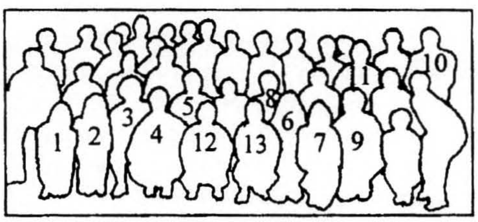
Case Study 2. Process Flowsheet Development for a Byproduct Purification

A process was being developed to implement a new catalyst in a synthesis process. The new catalyst produces the desired product (A) plus a significant quantity of a valuable byproduct (B), which needs to be purified in order to be marketable. The byproduct can be separated from the major product stream relatively easily, but is contaminated with several other compounds, including an undesirable byproduct (C). Byproducts B and C are difficult to separate because they differ only in their degree of saturation. The clients wanted to determine the optimum plant configuration and operating conditions to purify byproduct B.

The students studied previously conducted experiments and process simulations on azeotropic distillation as a potential separation method for B and C and found that the physical property data initially used in the simulations were inadequate, leading to gross overestimation of the separation efficiencies. They used refined physical property estimates to conduct Aspen Plus simulations, obtaining results matching experimental data, which showed this technique to be infeasible.

They conducted an in-depth literature review of other possible separation techniques and discovered several possibilities that had not yet been considered. They investigated the feasibility of a range of techniques, with the assistance of information from the literature, Aspen Plus simulations, and consultations with experts at M.C.C. One new technique involving solvent extraction with a pH swing was found to be favorable. As a result of this discovery, measurements of the distribution coefficients of B and C in an appropriate extractant were rapidly commissioned to provide the necessary data for the students to simulate this process. They used these data in Aspen Plus simulations to design and optimize the flowsheet for the byproduct purification section of the plant. The new process required many fewer unit operations than previous proposals to meet the product specifications and also simultaneously removed other contaminants from byproduct B.

The students conducted preliminary economic analyses on the proposals investigated and made recommendations of further refinements needed in the simulations of the most favorable proposal. As a result of the students' findings, the clients switched their attention from the unfavorable azeotropic distillation initially proposed to a simpler and more cost-effective extraction process.



After their final oral project reports, the M.I.T. students (Celia Huey, 1; Karen Zee, 2; Justin Zhuang, 3; Alejandro Cano-Ruiz, 4; Thomas Gubiotti, 5; Susan Dusenbery, 6; Tanya Moy, 7) with the Practice School Directors (Alan Hatton, 8; Andrea O'Connor, 9; Angelo Kandas, 10) and M.C.C. staff members (including Plant General Manager, Mitsuyoshi Mitsuoka, 11; D.E.R.C. Director, Hiroyuki Kobayashi, 12; D.E.R.C. Deputy Director, Yukikazu Natori, 14).

and traveling around the local area where English was rarely spoken. Bus transport, provided by M.C.C. to all employees, was used to travel to the plant on weekdays, and bicycles were used on the weekends.

During the first week in Japan, prior to the start of the station operations, the students were taken on a three-day excursion to Kyoto and Nara by bullet train. This trip served as an excellent way for the students and directors to get to know each other, and to learn a little about the culture and history of Japan. Escorted by a member of the Personnel Section of M.C.C., the students learned about some of the significant sites in these two old capitals of Japan and gained confidence in the day-to-day living skills they would need throughout their stay in Japan.

The station facilities provided by M.C.C. included desks in a large, open-plan office with other M.C.C. employees, and company uniforms (a symbol of belonging to the organization). The students worked within a firmer daily schedule than at U.S. stations, as they used the company bus for commuting between the plant and the apartment complex, and required an English-speaking staff member to be on site with them when working on weekends, in case of emergencies.

At this station, the students met regularly with their project teams, comprising several M.C.C. engineers and scientists for each project. They also benefited from interaction with DERC senior engineers and technical specialists in areas such as modeling and process optimization. M.C.C. staff members from other sections, and even other sites, attended the students' oral presentations, and the students had an opportunity to make poster presentations in an annual M.C.C. poster session, further broadening their exposure to company personnel. It was not generally possible, however, to establish meaningful interactions between the students and operators because of language barriers. Thus, all plant information was gained via the project sponsors, and instructions for experiments or plant trials run by the students had to be communicated to the operators via the sponsors. While this is a drawback of the language barrier, it is not atypical for consultants working in foreign countries, and it was good experience for the students, giving them an appreciation of the difficulties this can generate.

Working at a Practice School station is often a time of stress for students, and being in a foreign country can exacerbate this. Hence, a special effort was made to ensure that some time for relaxation away from the workplace was set aside each week. In order to avoid any feelings of isolation, as well as to make the most of the opportunities to experience Japanese life and culture, activities or excursions were

Continued on page 171.

THE GREEN SQUARE MANUFACTURING GAME

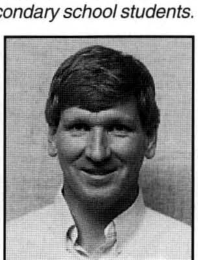
Demonstrating Environmentally Sound Manufacturing Principles

Suzanne S. Fenton, James M. Fenton
University of Connecticut • Storrs, CT 06269-3222

The Green Square Manufacturing Game addresses several issues of engineering education. The first is the need to instill future engineers with "environmentally sound" thinking. The concept of pollution prevention should be taught across all disciplines of engineering, and an ideal place to introduce this concept is in the freshman engineering curricula. The Green Square Game is perfectly suited for such an application and can be "played" in a single class period or spread over two class sessions, with a historical perspective of US environmental laws included throughout the game.

Another issue the game addresses concerns hands-on learning versus passive learning. It provides hands-on learning and group design with minimal fuss or preparation time, followed by an open discussion of the results. This approach increases enthusiasm for problem solving, is easy to implement, and uses inexpensive, readily available supplies.

***Suzanne S. Fenton** earned her PhD in chemical engineering at the University of Illinois and her BS in environmental engineering from Northwestern University. In addition to her responsibilities as Assistant Head of the ChE Department at Connecticut, she provides innovative hands-on classroom instruction for undergraduate engineering and secondary school students.*



***James M. Fenton** is Professor and Acting Head of Chemical Engineering at the University of Connecticut. He earned his PhD from the University of Illinois and his BS from the University of California, Los Angeles, both in chemical engineering. He is Director of the Pollution Prevention Center at Connecticut and does research in electrochemical engineering.*

The Green Square Game can also be easily adapted for use at the secondary-school level as a tool to raise awareness (and the status) of the engineering profession among high school students. In this case, a faculty member or a secondary school teacher can lead the game, providing high school students with a challenging and thought-provoking glimpse of engineering relevance in today's world.

The game is played in two sections. During the first round, students are told that the year is 1953. They are split into different "companies" (of three, four, or five students each) that manufacture green squares. Each of the companies is competing to win YOU (the instructor) as their client. YOU want to purchase green squares of a particular shade and size (5 cm x 5 cm white paper squares painted green on one side). The companies are put to work trying to replicate the sample green square by using powdered blue and yellow tempura paint. No mention is made of environmental impact or waste disposal. Then, during the second round, the year is changed to 1998. Again, YOU are the customer requesting green squares, but this time the constraint of waste minimization is placed on the "companies" and students must try to produce the green square with as little waste generation as possible.

The game is an ideal hands-on classroom project for freshman engineering and high school students; it highlights waste minimization, pollution prevention, and industrial ecology and offers valuable experience in group problem solving. Faculty members at the University of Connecticut and secondary school teachers throughout the state have used the game with great success. Secondary school teachers have been introduced to the game as "participants" during university outreach activities. The game was originally developed by WRITAR[1] as a role-playing exercise to train state regulatory staff.

GOALS AND OBJECTIVES

The purpose of the game is to give students a taste of how waste minimization influences a manufacturing process (the production of green squares). This mock process is also intended to help participants become more aware of sources of waste, options for waste minimization, resistance to change, and the importance of communication and cooperation in waste-reduction efforts.

Underlying objectives of the exercise are to demonstrate the technical challenges (and frustrations) of reducing waste in an industrial setting and to demonstrate the non-technical issues that influence waste reduction efforts, including customer demands and competition.

INSTRUCTIONS

1. Assemble participants into "companies" of three, four, or five students each and seat them around the "production floor" (flip chart paper spread on a table is the best production floor since it lies flat and "waste" is easily seen; a sheet of brown wrapping paper, a cut-open paper grocery bag, or a sheet of newspaper could also be used).
2. Each group is a "company" that manufactures green squares.
3. Tell participants that you are a potential client who would like to purchase green squares that look like the model shown (a prepared sample). You will be distributing the green squares overseas and are looking for a new supplier for a $2-million contract next year. You are asking the "companies" to compete to win your business.
4. Ask the groups to invent their own company name and write the team names on a flip chart, blackboard, or viewgraph.

FIRST ROUND

1. The year is 1953.
2. The criterion for the competition is that the company's product should exactly match the model shown (including dryness) in the allotted amount of time.
3. Companies use the materials provided (powdered blue and yellow tempura paints, paint brushes, mixing cups, water, white paper, etc.) to produce a perfect green square. They are given 10 to 20 minutes (depending on the time available) to complete the project.

At the end of the "production time," instruct the teams to stop. Inspect each team's product and evaluate its efforts using the criteria suggested in Table 1 (or substitute your own criteria). As the customer, you must assign value to criteria as you see fit. If time permits, students may also be given an opportunity to evaluate their own and fellow companies' performances. Rate or rank-order company performance based on the evaluations and instruct the teams to clean up.

Discuss the results of the first round. Discussion questions for it might include:

- Was it quiet while the exercise was going on?
- Was the project time consuming?
- What approaches did groups use to produce the square? Was a lot of planning involved?
- Did students work as a team?
- Was waste a concern?
- How much waste did the groups generate (production floor cleanliness; number of contaminated brushes, cups, and spoons; cleanliness of the back of the green square; left-over green paint; contaminated hands, clothing, etc.)?
- Were raw materials wasted?

SECOND ROUND

1. The year is 1998.
2. Again, the goal is to manufacture green squares—but with an additional constraint. In addition to product quality and time, companies must consider environmental impact.
3. Explain that any surface or object that becomes contaminated with paint (of any color) becomes "hazardous." This includes all materials, hands, clothing, table surface, and floor. Explain that teams will be evaluated on their ability to paint the square green while generating the least amount of "hazardous" waste.
4. Let the teams begin production. Again, allow 10 to 20 minutes to complete the exercise.

At the end of the "production time," instruct the teams to stop. Again, inspect each team's product and evaluate its efforts. Table 1 contains a list of possible evaluation criteria for this round. It is easiest to give each criteria equal weight. Rate or rank-order company performance based on the round-two criteria and instruct teams to clean up.

As an alternative to this scheme, more "realism" can be injected into the project by assigning dollar values (based on product quality) and costs to the items listed in Table 1. Company performance can then be judged by profits (*i.e.,* value less cost).

TABLE 1
Evaluation Criteria

First-Round Evaluation Criteria
- Color and size match model
- Color consistency
- Dryness of sample
- Cleanliness of back of sample

Second-Round Evaluation Criteria
- Color and size match model
- Color consistency
- Dryness of sample
- Cleanliness of back of sample
- Amount of raw material used
- Production floor cleanliness
- Number of contaminated brushes
- Number of contaminated cups
- Number of contaminated spoons
- Left-over paint
- Contaminated hands, clothing, etc.

For example, values of $1, $0.50, and $0.00 can be given for perfect color match, acceptable color match, and unacceptable color match, respectively. Equal valuations can be assigned for color match, consistency, dryness, and cleanliness (a perfect sample would be worth $4.00). Similarly, costs can be assigned to raw materials (paint), equipment (brushes, cups), labor, and environmental decontamination ($/area of contamination?). Time permitting, different "value and cost" schemes can be used in judging performance to illustrate the interactions between environmental concerns and engineering design.

Second-round discussion could include:

- Was it quiet while the exercise was going on? Which production round was more time consuming?
- Did the second round require more planning? Did the students work more as a team?
- How did the focus change?
- What techniques were used to minimize waste generation? Which ones were the most successful?
- How much waste minimization was accomplished? How is it quantified? Is zero discharge possible?
- How was the product quality affected during the second round?
- Solicit ideas on how to dispose of waste generated by each company.
- If incineration is recommended, what might happen to the hazardous material? Solicit ideas on how to dispose of toxic ash and air pollution.
- If landfill is recommended, again ask what possible environmental impact may result. Solicit ideas on how to clean up contaminated water and soil, and on what should be done with the hazardous remains.
- Is there a compromise between product quality, cost (time), and environmental concerns?
- Where does the garbage that the students generate at home go?
- Encourage students to research industries in their own communities that generate air, water, and soil pollution and where that waste is disposed.

ADVICE TO INSTRUCTORS

Materials (for each round)

- Small paper cups (about 3-ounce size), two for the powdered paints, one for water, and three for mixing
- 1 tablespoon of powdered blue tempura paint in a paper cup is provided to each company
- 1 tablespoon of powdered yellow tempura paint in a paper cup is provided to each company
- Plastic spoons (popsicle sticks or plastic spatulas)
- Inexpensive watercolor brushes
- White construction paper
- Scissors
- "Production Floor" (a sheet of brown wrapping paper, a cut-open paper grocery bag, or a sheet of newspaper spread on a flat table).

***Short Version* (less than 50 minutes)**

To play the game in a short time period, it is best for the instructor to pre-cut the squares and to have two production floors for each company set up (one for each round) before the students arrive. The students should be pre-assigned to a company and the company name should be selected in advance of the class period. Restrict the production runs of each round to 10 minutes and have prepared score sheets available for judging performance. The first- and second-round discussions can be combined if necessary, and any issues not discussed in class can be given as homework.

***Long Version* (less than 120 minutes)**

To play the game in a longer period, a lecture (Historical Perspective: U.S. Industry and the Environment) is given so the students are brought from 1850 up to 1953 before round one is played. Then the lecture is continued from 1960 up to today before round two is played. A brief description of this historical perspective is given below. It is focused on industrial pollution, but keep in mind that a large percentage of waste was (and still is) generated by non-industrial sources. Historical information can be found in references 2 through 6.

Lecture

1850-1900 • *U.S. industrial waste regulation between 1850 and 1900 was minimal. Industrial expansion and population growth resulted in severe pollution in urban areas. The major industrial chemicals manufactured during the period from 1850 to 1900 were caustic soda (NaOH), chlorine (Cl_2), soda ash (Na_2CO_3), fertilizers, ammonia, acids (H_2SO_4, HCl, HNO_3), refined petroleum products, soaps, steel and refined metals, paint, pulp and paper, and coal gas. Typical waste streams from these activities included heavy metals (including mercury and lead), polycyclic aromatic compounds, waste acids, pulp and paper liquors, solvents from petroleum and wood distillation, and aquatic nutrients such as nitrates and phosphates. Waste treatment techniques were rarely used during this period except for the recovery of valuable by-products, and waste streams were disposed of in the most convenient manner available. The first environmental law enacted in the U.S. was the Refuse Act of 1899 for the purpose of preventing impediments to navigation!*

1900-1930 • *From 1900 to 1930, industry focused on maximizing production. Factories became centralized in locations best suited for the particular type of product being made (e.g., Pittsburgh became the "Steel City"). Emerging technologies during this period included synthetic rubber, polymers and plastics, and metal finishing (electroplating). Typical waste streams from these new endeavors included aqueous heavy metals and metallic sludge, cyanide compounds, "off-spec" materials and products, and petrochemical by-products. Waste "treatment" during this period consisted of dumping solid waste into landfills and liquid waste into on-site ponds or lagoons. Urban population and pollution continued to grow at exponential rates, primarily due to spectacular increases in immigration and rural-to-urban migration. Pollution problems were regarded as nuisances, but no comprehensive environmental reforms were made concerning industrial discharge.*

1930-1950 • *The period from 1930 to 1950 saw many advances in chemical technology. Rapid-growth industries included pharmaceuticals, synthetic organic petrochemicals (pesticides, chlorinated compounds, polymers), detergents, cosmetics, and coatings. Breakthroughs in one area often provided abundant and inexpensive raw-material feedstock for many other operations. For these reasons, the variety, volumes, and toxicity of industrial waste streams were rapidly on the rise. Disposal was preferred to treatment because of economics and a lack of federal regulations. Disposal methods included the use of sludge ponds, dilution ("the solution to pollution"), deep-well injection, and ocean dumping. Most government regulations at the time were concerned with product quality and safety rather than environmental issues (Federal Food, Drug and Cosmetic Act of 1938, Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) of 1947).*

The first federal law dealing with conventional forms of water pollution (the Federal Water Pollution Control Act) was passed in 1948. It authorized funding for municipal sewage treatment plants and established broad authority to regulate industrial and municipal discharges through the National Pollution Discharge Elimination System (NPDES). States were given the job of issuing permits and enforcing compliance of this law, which dealt mainly with blatant and acutely toxic industrial discharges.

In the 1950s, an exponential increase in manufacturing occurred as a result of the healthy economy, a rapidly growing population, and product-hungry consumers. During this time, the prevailing government attitude was "If it's good for business, it's good for America," the prevailing industrial attitude was "Profits are high, regulations are few, and life is good!", and the prevailing consumer attitude was "Buy it, use it once, throw it away."

TABLE 2
Current Environmental Laws Affecting U.S. Industry

- Toxic Substances Control Act
- Clean Water Act
- Hazardous Materials Transportation Act
- Emergency Planning and Community Right-To-Know Act
- Federal Food, Drug, and Cosmetic Act
- Pollution Prevention Act
- Poison Prevention Packaging Act
- Marine Protection, Research, and Sanctuaries Act
- Clean Air Act
- Resource Conservation and Recovery Act
- Comprehensive Environmental Response, Compensation, and Liabilities Act
- Federal Insecticide, Fungicide, and Rodenticide Act
- Consumer Product Safety Act
- Federal Hazardous Substances Act
- Ports and Waterways Safety Act

1950-Present • *In the 1960s, U.S. industry continued to grow and prosper. Crude oil was practically free, so Americans were combusting it and polymerizing it as fast as they could. Environmental laws were few, and most discharges were unregulated. But the effect of pollution on the environment was becoming obvious—major rivers were catching fire, smog was causing significant health problems in many urban areas, fish were floating instead of swimming, and wildlife was disappearing.*

These and other problems resulted in public outrage and the demand for far-reaching environmental legislation. The United States Environmental Protection Agency (USEPA) was created by presidential order in 1970. It became the lead agency for the control of pollution of the nation's air, water, and land resources (a job previously relegated to the U.S. Department of Health Services and the Federal Water Pollution Control Administration). The USEPA was given authority to regulate the industrial community.

During the late 60s and throughout the 70s, many new environmental laws were enacted, including the Clean Air Act, Clean Water Act, Toxic Substances Control Act, and Resource Conservation and Recovery Act. Significant national policy changes such as removing lead from gasoline, removing phosphates from detergents, and banning a number of dangerous pesticides were also made during this time. Current laws affecting U.S. Industry are listed in Table 2.

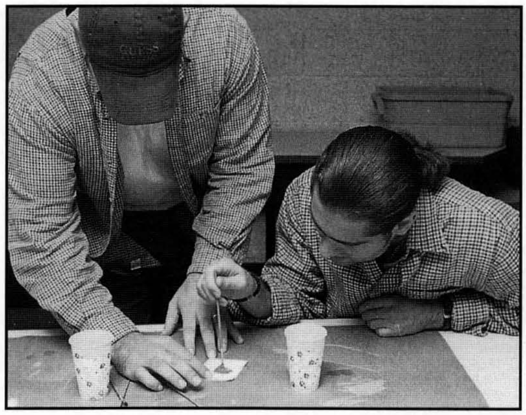
In 1980, a major piece of legislation, called the "Comprehensive Environmental Response, Compensation, and

Liabilities Act," was passed. It authorized the federal government to respond to spills and other releases of hazardous substances, established a fund for cleanup, and established industrial cost liability.

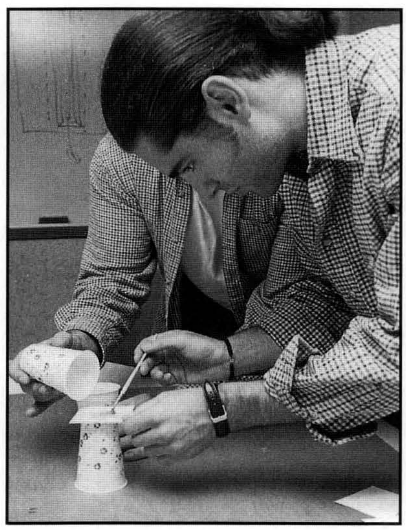
Additional environmental issues that reached public awareness in the 80s include airborne acids, heavy metals, oxidants, acid rain, stratospheric ozone depletion, global warming, the disappearance of municipal and hazardous waste land fills, ocean dumping, and other illegally dumped hazardous waste.

As a result of these and other problems, industries found themselves faced with lawsuits, protests, opposition to new plant sites, disputes over product approval, and more environmental laws.

Today, every aspect of doing business is affected by environmental concerns. Industrial expenses associated with environmental protection include the purchase and transport of regulated materials, consulting fees, air and water discharge permit fees, and administrative costs for permitting, reporting, monitoring, sampling, manifesting, and labeling. Additional costs to industry are incurred in the purchase of pollution-control equipment, taxes and insurance, penalties and fines, lawsuits, off-site transportation, treatment and disposal, on-site treatment and control, contaminated site cleanup, customer dissatisfaction with poor environmental policy, and long-term liability for waste disposal.



Students at work during round one.



Students during round two.

During the "long version" it is still best to have two production floors for each company (one for each round) set up before the students arrive. There is sufficient time to let the companies cut their own squares. The production runs of each round are now limited to 15 to 20 minutes.

Examples of Green Square "Innovations"

Typically in round one, the companies will mix paints in the extra cups provided, paint several squares, and paint the production floor while painting the edges of the square. Often, the production floor is used as a mixing area. Some groups may assign functions and work as teams, while others may produce squares as individuals.

In round two, expect more up-front discussion and more teamwork. Most of the innovation occurs in round two. Mixing typically occurs directly on the square, and the paintbrush may be the only tool. Holding the square so the edges can be painted without contaminating other surfaces or hands presents a challenge. Curiosity as to how the other companies manufacture their squares is also greater in round two ("industrial espionage").

Often the students will use other pieces of equipment. The fan on the viewgraph projector has been used to dry the green squares. Small containers such as lipstick lids have been used for mixing, and tissues are often used to wipe hands and spills. Occasionally these "outside" items have been used and then hidden from the instructor (illegally dumped hazardous waste!").

CONCLUSIONS

The Green Squares Manufacturing game is an excellent hands-on way to introduce the concept of pollution prevention to undergraduate engineering and secondary school students. The game demonstrates both technical and non-technical challenges of reducing waste in an industrial setting and makes participants more aware of sources of waste, options for waste minimization, resistance to change, and the importance of communication and cooperation in waste-reduction efforts.

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Internationalizing Practical Chemical Engineering Education

Continued from page 165.

organized for the students each weekend. A number of M.C.C. staff members often joined these activities, providing further opportunities for cultural interactions. Examples include a day trip to Hiroshima to tour the Peace Park and A-Bomb Museum, plus Miyajima Island, location of one of the "three best views in Japan"; trips to the beach; playing in an M.C.C. badminton tournament; and joining the traditional Bon Dance Festival.

PROJECT REVIEWS

The projects selected at the inaugural M.C.C. station were all ambitious and important to developments underway at the time. On the first day the students attended the plant, they were introduced to M.C.C. and the Mizushima Plant, including the personnel with whom they would interact, and to company regulations. They also received training in plant safety. Each group was then presented with a several-page problem statement, prepared by the Station Directors, describing the background of their allocated project. The specific project aims were stated and a suggested method of approach was provided. There were elements in each project, however, that were quite open-ended and required the students to develop their own plan of attack in consultation with their sponsors and the Station Directors.

Practice School projects are generally diverse and may include optimization of an operating plant, research, or design, or a combination of these. Two examples of projects undertaken and the work executed by the students are highlighted in the sidebar box, within the bounds of company confidentiality. One student observed that the "projects were very technical in nature, and our sponsors have given us a great deal of trust in executing them. I feel that we actually made a contributionty." Another student noted that "we were given real problems and were expected to give real solutions."

PROS AND CONS OF GOING INTERNATIONAL

The benefits of the experience of successfully completing a semester at Practice School stations were as strong as ever for the students who attended the M.C.C. station. The skills they gained included: problem solving in an industrial context; project planning and management under tight deadlines; application of integrated chemical engineering skills and engineering judgment; strength in written and oral communication; and enhanced teamwork and leadership abilities.

In addition, they gained an intangible but important insight into the operation of a major Japanese corporation from within. For both the students and the M.C.C. staff with whom they worked, the opportunity to form international networks and build understanding of their differences and similarities in culture, language, and business practices will be extremely valuable in their future careers.

There were some disadvantages that we were not able to overcome. In particular, the language barrier limited the M.C.C. staff members with whom the students could communicate. The project sponsors were very capable and enthusiastic to communicate in English, but many of the operators and technical staff were not able to interact with the students. This closed off a potential source of process information and kept the students from attempting the sometimes-difficult task of forging good working relationships with operators.

Factors such as this make the combination of experience at one U.S. station and one overseas station ideal. While these problems can be alleviated to some extent by considering language skills during the student selection process, it is unlikely that all students assigned to an international station will have a working knowledge of the language spoken at that facility. We will continue to provide such students with basic instruction in the language and culture of the host country.

CONCLUSION

The Practice School experience at M.C.C. in Japan demonstrated that operating an international industrial training station as part of a practical engineering education program can be highly successful. In spite of initial concerns over language and cultural barriers, the students' performance in the overseas environment was of the high standard expected in the Practice School program, and they also benefited greatly from exposure to and interactions within a major Japanese company. Despite the high intensity of the program and the stress of living in a new environment, the first students at the M.C.C. Practice School station all recognized the advantages of their overseas experience and were pleased to have had the double opportunity of Practice School training plus experience in industry overseas.

The Practice School intends to maintain a presence overseas; last year international industrial stations operated at Rhone Poulenc (France), Bayer (Germany), and again at M.C.C.'s Mizushima Plant. While it is important that the international stations never replace the U.S. stations completely, they make an excellent complement to students' experiences in the U.S.

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REMOVAL OF HEAVY METALS IN WASTEWATER BY ELECTROCHEMICAL TREATMENT

EDUARDO EXPÓSITO, MARINA INGLÉS, JESÚS INIESTA, JOSÉ GONZÁLEZ-GARCÍA, PEDRO BONETE, VICENTE GARCÍA-GARCÍA, VICENTE MONTIEL
Department of Physical Chemistry • Universidad de Alicante • Alicante, Spain

During the last decade, there has been increasing social preoccupation in industrialized countries with respect to environmental protection, resulting in progressively tougher legislation regarding waste deposits. The presence of heavy metals in wastewater constitutes one of the most important problems in environmental engineering today,[1] fundamentally due to their high toxicity and cumulative character. Contamination by heavy metals is principally a problem characteristic of industrial effluents, and the activities that generate dumps of this kind of contaminated material are both numerous and diverse: metallurgical processes, industries involving metal plating, pigmentation and dyes, and producers of cellulose acetate, accumulators and batteries, printed circuits, etc. Given that the great majority of metallic ions can be electrodeposited in a metallic form on a cathode, electrochemistry offers a way of treating almost all of these types of wastewater.[1-4]

On the other hand, when treating effluents it is normal to work with low concentrations of heavy metals in solution (less that 1000 ppm). When two-dimensional electrodes are used as cathodes, the low concentration originates transport problems of these ions to the cathode at high current densities. This fact makes it necessary to design electrochemical reactors capable of treating these types of effluents in an efficient way; that is to say, obtaining an almost total recuperation of the metal.

One very interesting option concerns the use of three-dimensional electrodes.[5-7] The principal characteristic of this type of electrode is that when it extends to three dimensions, it has a high active area on which the electrochemical reaction can take place; in our case, depositing of the metallic ion. The direct consequence of the high active area that these electrodes have is a decrease in the real current density when the deposit reaction takes place, even when working at high current intensities. This minimizes the problem of transport of the reagent to the electrode and permits almost total elimination of the metallic ions in the effluent to be treated.

The laboratory experiment described in this paper was developed for advanced students in chemical engineering or chemistry. It was designed for groups of three students each to perform during two periods of four hours each. The students must present a full report on the experiment at its end, including a description of the experiment's objective, the experimental plan, a description of the experimental system, a brief summary of the theory behind the experiment, presentation and treatment of experimental data, discussion of the results, and finally, any suggestions that might improve the experiment and a discussion of the sources of error.

The main objective of the experiment is to demonstrate an

Eduardo Expósito *received his BS in 1993 and his MS in 1994 from Córdoba University and is working on his PhD at the University of Alicante. His academic research involves wastewater treatment and organic electrosynthesis.*
Marina Inglés *received his BS in 1996 and his MS in 1998 from Alicante University. His academic research involves organic electrosynthesis.*
Jesús Iniesta *is a doctoral student at the University of Alicante. He received his MS in electrochemistry from the same university and has done work in the electrochemical treatment of hazardous organic compounds.*
José González-García *received his degree in chemistry in 1990 and his PhD in 1998 from the University of Alicante, where he is currently a faculty member. His academic interests are in electrochemical engineering and applied electrochemistry.*
Pedro Bonete *received his degree in chemistry in 1990 and his PhD in 1995 from the University of Alicante, where he is currently a faculty member. His academic research involves organic and electroorganic synthesis.*
Vicente García-García *received his PhD in chemistry in 1991. His research interest is in applied electrochemistry. He has worked with laboratory and pilot plant experiments.*
Vicente Montiel Leguey *is Associate Professor in the Department of Physical Chemistry at the University of Alicante. His research interests are in electroorganic synthesis and wastewater treatment by electrochemical methods.*

electrochemical application for solution of the very real problem of removing heavy metals in effluents. In addition, and following a predominantly applied method, the economic parameters of the experiment are calculated. At the end of the experiment, the students must understand and be familiar with the different electrochemical processes (oxidation and reduction reactions, Faraday's laws, etc.), parameters, and magnitudes (current density, cell voltage, etc.).

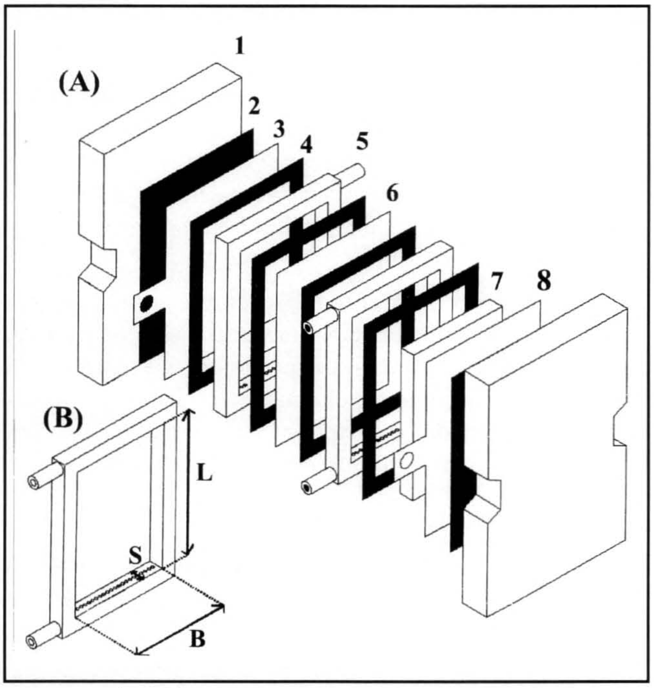

Figure 1. (A) *Filter-press reactor scheme: 1. Back plates; 2. Insulator sheet; 3. DSA-O_2; 4. Sealing sheet; 5. Solution frame; 6. Anionic-exchange membrane; 7. Carbon felt; 8. Graphite plate.*
(B) *Scheme of the filter-press reactor dimensions.*

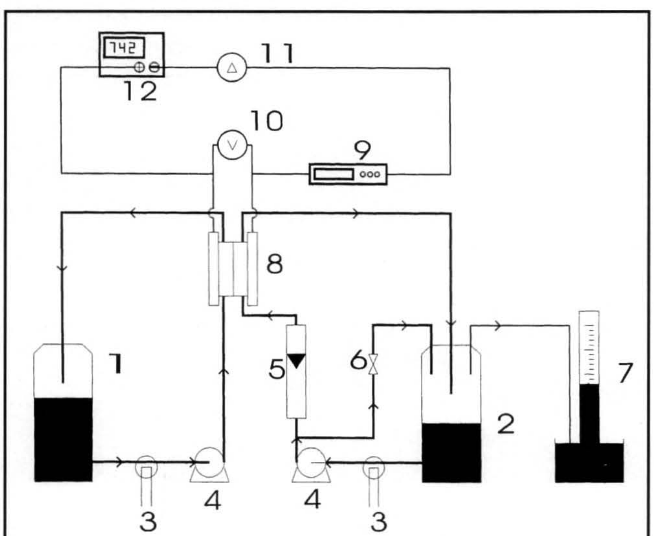

Figure 2. *Scheme of the experimental system: 1. Anolyte tank; 2. Catholyte tank; 3. Heat exchanger; 4. Pumps; 5. Flowmeter; 6. Bypass; 7. System for gas measuring; 8. Filterpress reactor; 9. Coulombimeter; 10. Voltmeter; 11. Ammeter; 12. Current feeder.*

The experiment concerns elimination via electrochemical treatment of the cation Cu^{2+} in a synthetic effluent, using a three-dimensional electrode as the cathode. Later, treatment of the effluent was carried out using a two-dimensional electrode and comparing the results obtained in both experiments. Finally, the economic parameters of the process (current efficiency, energy consumption, etc.) were calculated for the experiment carried out with the three-dimensional cathode.

EXPERIMENTAL PROCEDURE

Description of the Experimental Assembly

The electrochemical reactor used was a filter-press-type reactor (see Figure 1) with separate anodic and cathodic compartments. Reactor dimensions were: length (L), 9 cm; width (B), 7 cm; height (S), 1 cm. As can be seen in the figure, this kind of reactor has a sandwich-type structure where the electrodes are placed at the reactor extremes. Each compartment consists of a flow distributor (made of polypropylene) where the solution flows parallel to the electrodic surfaces. The anodic and cathodic compartments are separated by a membrane. The figure shows how all the described elements are separated by sealing sheets to prevent the escape of solution.

The cathodes are a carbon felt (supplied by Carbone Lorraine) with an active electrode area per unit volume of 221 - 7 cm^2/cm^3 as the three-dimensional cathode and a graphite plate as the two-dimensional cathode. In the experiment with the three-dimensional electrode, the graphite plate is used as a current collector. As the anode, a DSA-O_2 electrode (Dimensionally Stable Anode for oxygen evolution) supplied by METAKEM (Usingen, Germany) was used in both experiments. The separator was a SIBRON 3457 anionic exchange membrane supplied by Ionac Chemical Company (New Jersey). The whole structure is placed between two steel plates where it is pressed to avoid solution escape. As shown in the figure, the only difference between the configuration of the reactor employed in the two experiments is the introduction of the three-dimensional electrode.

Figure 2 shows a simplified diagram of the experimental system. It includes a filter-press cell, electrolyte tanks, and magnetically driven pumps. The system permits control and measurement of the temperature and the catholyte flow by means of two heat exchangers and a flowmeter, respectively. The gases generated over the cathode were collected in an inverted burette to measure their volume. To prevent gas escape, the cathodic branch of the system was hermetically sealed. This branch also had a bypass to secure complete homogenization of the catholyte solution. The necessary electrical instrumentation consisted of a 3A-30V DC power supply, two multimeters to measure the intensity flowing and the cell voltage, and a coulombimeter with a 0.1-1A shunt to measure the charge passed.

Analysis of the Cu^{2+} concentration in the samples was made using the ICP (Inductive Coupled Plasma) with an ICP Perkin-Elmer Optima 3000. Since most undergraduates do not have an ICP readily available, they could also analyze the Cu^{2+} concentration with the colorimetric method of the Bicinchoninate.[8]

Carrying out the Experiments

The experimental conditions under which the two experiments were carried out are shown in Table 1. Prior to each practice session, the professors must prepare the anolyte and catholyte solutions and register the calibration curve of the ICP analyzer in order to facilitate analysis of the samples that will be taken by the students. The Cu^{2+} calibration curve is linear over the entire concentration range of Cu^{2+} (0 - 1000 ppm Cu^{2+}), and it is not necessary to dilute the samples taken during the experiments.

First Session • In this session, the students must carry out the elimination using a three-dimensional cathode. Before the experiment starts, it is helpful for the professor to show the students a disabled filter-press reactor so they can better comprehend the structure and method of operation of a filter- press reactor.

First, a sample of 1 ml of catholyte must be taken before its introduction into the system in order to know the exact initial concentration of the Cu^{2+}; this sample is labeled "sample 0." After that, the anodic and cathodic branches must be filled and washed with distilled water. Then the system is emptied. The catholyte and anolyte solutions can then be introduced into the corresponding deposits and the pumps connected; the catholyte flow is adjusted to the required value, and after a few minutes the system reaches the working temperature of 30°C. At that moment, a 1-ml volume sample of the catholyte solution is extracted and labeled "sample 1." After that, current (0.63A) is made to flow through the system.

The experiment is carried out for approximately one hour. Every five minutes, 1-ml-volume samples are taken until the end of the experiment at 2500 C of passed charge (this charge is rather more than the 150% charge necessary to deposit the 0.5g Cu^{2+} initially present in the catholyte, thus assuming a 100% current efficiency in the copper-deposit reaction). For each sample, note is taken of the values of time, cell voltage, quantity of charge circulated, and the volume of gas originated onto the cathode. At the end of the experiment, the volumes of the anolyte and catholyte are measured and a sample of the anolyte solution is taken to check the presence of Cu^{2+} that may have passed through the membrane separator. After that, the system is washed several times with distilled water. The electrochemical reactor must be filled with water until the next session.

Hydrogen is a flammable gas. Although the volume of H_2 generated during the experiments is small, care is necessary and the burette where the H_2 is collected must not be exposed to heat.

During the session, the Cu^{2+} concentration of the samples must be measured. The catholyte solution initially has a light-blue color due to the presence of ions $[Cu(H_2O)_6{}^{2+}]$ in solution. As copper is deposited on the cathode, the solution gradually loses its blue color until it is completely colorless at the end of the experiment.

Second Session • Prior to the second session the professors must remove the three-dimensional electrode from the reactor and prepare the system. During this session, the students must carry out the elimination of Cu^{2+} using a two-dimensional cathode. The experiment is carried out by using the same procedure as was used in the first session.

RESULTS AND DISCUSSION

1. The most important charge-transfer processes that take place inside the electrochemical reactor can be seen in Figure 3.
2. At this point, it is possible to observe the differences found between using a three-dimensional and a two-dimensional cathode to remove Cu^{2+}. Figure 4 shows Cu^{2+} concentrations in the catholyte vs time. When the three-dimensional carbon felt cathode was used, the final Cu^{2+} concentration in the catholyte was less than 1 ppm. On the other hand, when the two-dimensional graphite cathode was used, the final Cu^{2+} concentration in the catholyte was approximately 50% of the initial concentration.

Table 2 shows the values of time, concentration of Cu^{2+} in the catholyte, volume of H_2 generated, charge passed, and the average cell voltage at different times of electrolysis. The results up to now show how well a three-dimensional electrode behaves in the elimination of heavy metal ions

TABLE 1
Experimental Conditions of the Cu^{2+} Removal Experiments

Operation Mode	Galvanostatic
Catholyte (V:0.51)	8 x 10^{-3}M $CuSO_4$ (1g/1 Cu^{2+}) + 0.5M Na_2SO_4 + 0.05M H_2SO_4
Anolyte (V:0.51)	0.5M Na_2SO_4
Temperature	30°C
Current Density	10 mA/cm^2 (current: 0.63 A)
Catholyte Flow	50 1/h
Total Electrical Charge	2500C

in solution versus the use of conventional two-dimensional electrodes in which the reaction of the formation of H_2 in the cathode is very important and the Cu^{2+} concentration decreases very slowly, as explained at the beginning of this article.

Table 3 shows the charge balance with respect to the electrodeposited Cu and generated H_2 at different times of electrolysis. Moreover, it is interesting in the experiment with the three-dimensional cathode to do the calculations at the point where the copper is eliminated, at approximately 45 minutes.

From the difference in Cu^{2+} concentration between sample 0 and sample 1, we may calculate the real volume of catholyte. It is interesting to note that the initial Cu^{2+} concentration in the experiment with the two-dimensional cathode is higher than the initial Cu^{2+} concentration measured in the experiment with the three-dimensional cathode. This fact can be explained because the carbon felt used as a three-dimensional electrode has a high porosity and retains a high volume of distilled water in the preliminary washing stage.

The principal error during the calculation of the charge balance is caused by the charge employed in the reduction of the O_2 present in the catholyte, which is not experimentally measured by the students. But this error is not too high due

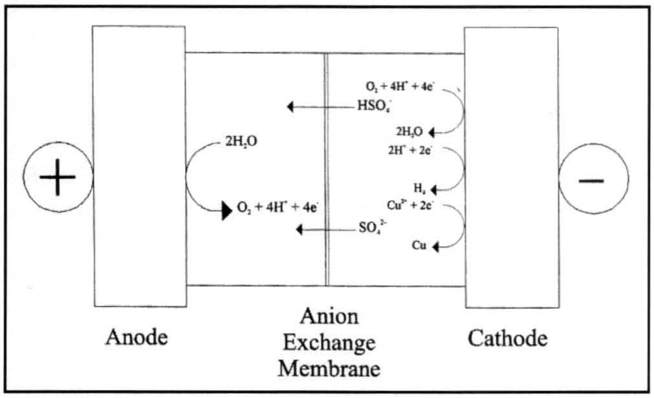

Figure 3. *Charge transport processes inside the filter-press reactor.*

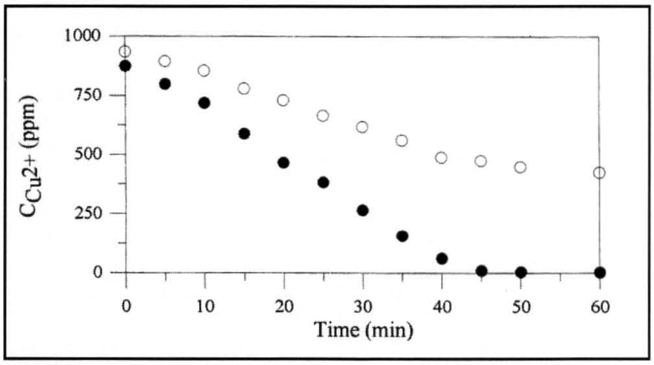

Figure 4. *Representation of Cu^{2+} concentration (ppm) vs. time (min) during the experiments.*
● - carbon felt; ○ - graphite plate

to the low concentration of O_2 in solution, and therefore it can be disregarded. Other optional methods are: give this value to the students, or before the experiment eliminate the O_2 in solution by bubbling the catholyte with N_2 for approximately 45 minutes, increasing the duration of the practice session in this way.

One of the most important experimental errors appears in the charge balance if the cathodic system is not hermetically closed—the measure of volume of generated H_2 will be incorrect. Close attention must be paid to this, especially during the sampling, to avoid any type of gas escape.

On the other hand, in the analyses of the anolyte samples taken at the end of the experiments, the presence of Cu^{2+} ions was not detected. This fact indicates that during the experiments, these ions did not pass through the membrane separator. This is logical due to the short duration of the experiments and the use of an anionic-exchange membrane.

Finally, the calculations corresponding to the economic parameters of the process for the experiment using the three-

TABLE 2
Parameters Measured in the Cu^{2+} Removal Experiments

Time (min)	Charge passed (C)	Cu^{2+} concentration (ppm)	Volume of H_2 (ml)	V_{cell}(V)
Three-Dimensional Cathode				
sample 0	-	995	-	-
sample 1	-	873	-	-
20	760	485	0	2.06
40	1520	81	11	2.16
45	1750	5.2	24	2.39
60	2280	1.3	78	2.42
Two-Dimensional Cathode				
sample 0	-	1010	-	-
sample 1	-	934	-	-
20	760	735	40	3.22
40	1520	511	87	3.27
60	2280	405	158	3.32

TABLE 3
Charge Balances of the Cu^{2+} Removal Experiments

Time (min)	Charge passed (C)	Charge Used in Cu^{2+} reduction (C)	Charge Used in H_2 generation (C)
Three-Dimensional Cathode			
20	760	683	-
40	1520	1380	87
45	1750	1510	190
60	2280	1515	620
Two-Dimensional Cathode			
20	760	343	317
40	1520	716	690
60	2280	892	1254

dimensional electrode are shown in Table 4. The following expressions are used to calculate the characteristic economic parameters of this electrochemical process.

Current Efficiency • This parameter relates the total charge passed with the charge used in depositing copper.

Current Efficiency Cu(CE%) =(Charge used in depositing copper/Charge passed) x 100

Energy Consumption • This is the energy necessary to deposit a certain amount of copper. It is normally expressed in kilowatt-hour (kWh) per kilogram (kg) of product obtained.

$$\mathrm{kWh} = V_{\mathrm{cell}}(\mathrm{V}) \times \mathrm{I(A)} \times \mathrm{T(s)} \times \frac{1\ \mathrm{kW}}{10^3\ \mathrm{W}} \times \frac{1\ \mathrm{h}}{3600\ \mathrm{s}} =$$

$$V_{\mathrm{cell}}(\mathrm{V}) \times \mathrm{Q(C)} \times \frac{1\ \mathrm{kW}}{10^3\ \mathrm{W}} \times \frac{1\ \mathrm{h}}{3600\ \mathrm{s}}$$

V_{cell} changes along the experiment. The correct expression of this parameter is

$$V_{\mathrm{cell}} = \frac{1}{T}\int_0^T V(t)dt$$

Nevertheless, the variation of V during the experiment is not very important, and to simplify the calculation of kWh, an average value can be used.

$$\mathrm{kg_{Cu}} = \text{number of deposited moles of Cu} \times \mathrm{At_{wt}Cu(g)} \times \frac{1\ \mathrm{kg}}{10^3\ \mathrm{g}} =$$

$$\mathrm{Q(C)} \times \frac{b}{n} \times \frac{\mathrm{CE\%} \times 10^{-2}}{F} \times \mathrm{At_{wt}Cu(g)} \times \frac{1\ \mathrm{kg}}{10^3\ \mathrm{g}}$$

The expression for energy consumption is

$$\frac{\mathrm{kWh}}{\mathrm{kg_{Cu}}} = \frac{2680.55 \times V_{\mathrm{cell}}}{\mathrm{At_{wt}Cu} \times \mathrm{CE\%} \times \frac{b}{n}}$$

where Q is the charge passed, I is the current, T is the time of electrolysis, V_{cell} is the average value of the electrochemical reactor voltage, $At_{Wt}Cu$ is the atomic weight of copper, b is the stoichiometric coefficient of metallic copper in the deposit reaction (in our case 1, Figure 3), and n is the number of electrons exchanged in the reaction (in our case 2).

It can be seen in Table 4 that the two calculated parameters are quite constant until 45 minutes. By this time, all the copper is deposited over the cathode. At that time, the formation of H_2 becomes important and the economics parameters become worse.

TABLE 4
Current Efficiency and Energy Consumption of the Cu^{2+} Removal Experiment with a Three-Dimensional Cathode

Time (min)	Current efficiency %	Energy consumption (kWh/kg_{Cu})
20	87	2.00
40	90	2.03
45	86	2.34
60	68	3.00

STUDENT REPORTS

1. First, the students must give a description of the experimental system and a brief summary of the theory behind the practice.
2. The students must have a clear comprehension of the charge-transfer processes that take place inside the filter-press reactor. In this way they must sketch a scheme similar to Figure 3. At this point, the professor can ask them some additional questions such as "Why do we use an anionic-type exchange membrane as the separator?" and "What will happen if we use a cationic-exchange membrane?".
3. The next step is to compare and explain the differences found between using a three-dimensional cathode and a two-dimensional cathode with respect to the recovery of copper. The students must represent Figure 4 and do the charge balance using the measured experimental data in the same way as mentioned previously. At this point, the question "What will happen if we bubble N_2 inside the catholyte solution?" can help the students detect the influence of the dissolved O_2.
4. Then the students should calculate the economic parameters of the experiment.
5. The last point is a critical evaluation of the practice and discussion of the sources of error.

SUMMARY

Student reaction to the experiment has been very satisfactory. The main importance of the practice session is that it tackles the real problem of treating effluents containing heavy metals. It also achieves the goals mentioned in the first paragraphs of this article. The students assimilated the basic theoretical concepts of electrochemistry (charge balances, charge and mass transport processes, Faraday's laws, etc.) and they familiarized themselves with the use of the instruments used in applied electrochemistry (power supplies, multimeters, coulombimeters, etc.).

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