Featuring...

Ronald W. Rousseau
of Georgia Tech

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PARTICLE SCIENCE AND TECHNOLOGY

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and Chemical Engineering at...

MISSISSIPPI STATE UNIVERSITY
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Mississippi State University

Chapel of Memories, constructed from bricks salvaged from original MSU men's dormitory that burned down in 1959.

REBECCA K. TOGHIANI
Mississippi State University • Mississippi State, MS 39762-9595

Mississippi State University (MSU), established in 1878 as the Mississippi Agricultural and Mechanical College, is located just east of Starkville, Mississippi. MSU is the largest of eight institutions of higher learning in the state of Mississippi and is the land-grant institution in Mississippi. Home to the Bulldogs (or "Dawgs," as they are more affectionately known around campus), MSU attracts quality students from Mississippi as well as from the surrounding states. It has grown from 334 men in 1878 to 14,862 undergraduate and graduate students with 828 teaching faculty for the 1997-98 academic year.

MSU has long been synonymous with engineering education in Mississippi and in the Southeast. The School of Engineering was established in 1892 by MSU's first president, Stephen D. Lee. In 1895, the first eight undergraduates pursuing the curriculum titled "General Engineering" were awarded degrees. Women were first admitted to the University in 1934, but could not live on campus as there were no women's housing facilities available. Alumni from the early years at MSU fondly remember "Old Main," which was the largest men's dormitory in the U.S. during its time. Old Main burned in 1959, and the bricks salvaged from its remains were used to construct the Chapel of Memories on campus.

The College of Engineering enrollment today stands at 2233 undergraduates and 268 graduate students, with 303 BS degrees, 116 MS degrees, and 18 PhD degrees having been conferred for the 1996-97 academic year. Enrollment of underrepresented groups in the College has grown at a rapid pace over the past two decades, and in 1990 the College of Engineering at MSU was recognized as one of the top thirteen producers nationwide of BS-level engineers of African-American descent.

The College of Engineering is also home to the National Science Foundation Center for Computational Fluid Simulation, the Diagnostic Instrumentation and Analysis Laboratory (DIAL), and the Raspet Flight Research Laboratory. The NSF Center is one of twenty-five engineering research...
centers across the United States with research efforts directed at enhancing global competitiveness of U.S. industry and agencies by reducing the time and cost for performing complex field simulations for engineering analysis and design. DIAL is funded through the Office of Environmental Management in the U.S. Department of Energy and has the mission of developing modern diagnostic techniques to monitor, control, and optimize environmental remediation processes. DIAL has recently moved into a new 54,000 ft² laboratory and educational facility located at the Mississippi Research and Technology Park adjacent to the MSU campus. The Raspet facility is the largest and best-equipped university flight research facility in the U.S. and is located at Bryan Field, just on the west side of Starkville. Faculty across the college and university engage in interdisciplinary research efforts through these research centers.

EXCITING TIMES AT MSU

The past decade has been one of tremendous growth and change at MSU. Improvements in facilities either recently completed or just underway include: the NSF Engineering Research Center, the DIAL Laboratory, a $15-million expansion and renovation of the Mitchell Memorial Library, the Joe Frank Sanderson Center (a recreational sports complex), renovation of the Hand Chemical Laboratory, the T.K. Martin Center for Technology and Disability, and the Dave C. Swaim Chemical Engineering Building.

Dean A. Wayne Bennett was named Dean of the College of Engineering in 1996 and through his leadership the framework has been laid for significant enhancements to the undergraduate and graduate programs in the College of Engineering with a $4.6-million grant from the Hearin Foundation. College faculty are excited about the change and opportunities that our undergraduate and graduate programs will undergo in the areas of global awareness, entrepreneurship, interdisciplinary activities, computation skills, and communications skills over the next five years.

The University’s 16th president was named this past fall. Dr. Malcolm Portera began his tenure as President of MSU on January 1, 1998. The coming decades offer much excitement and continued growth for the Chemical Engineering Department.

HISTORY OF THE DEPARTMENT

Chemical engineering at MSU made its debut in 1935 as a curriculum offering through the Department of Chemistry. The first program lacked many of the features present in modern-day chemical engineering programs and, as was common in those days, encompassed the field of industrial chemistry. In 1936, courses in unit processes, industrial stoichiometry, and chemical plant design were added to the curriculum, and in 1939, a state-of-the-art course, “Slide Rule,” offered by the Physics Department, was added to the chemical engineering curriculum. The catalog curriculum description for chemical engineering noted that “those who wish to make careers in this field will naturally look forward eventually to opportunities for graduate study.” Obviously, the opportunities for chemical engineers in industry have grown since that time.

Harold E. Graves, Associate Professor of Chemical Engineering, was the only faculty member in the Chemistry Department who taught ChE courses (all seven of them!) in those early years. It wasn’t until 1942 that the Department of Chemistry became the Department of Chemical Engineering. The first six graduates to complete the chemical engineering curriculum matriculated in 1938, and among them was Robert Lamar Pigford, who graduated with “Special Honors.”

Throughout the forties and fifties, chemical engineering was staffed by one, at most two, faculty members who taught all of the required courses. Graves left the university in 1939 and Laddie F. Dobry took his place as the sole chemical engineering faculty member. In 1940, Dillon Evers joined Dobry, but he soon went on leave and remained on leave through 1943. Michael G. Pelipetz came in 1942 and stayed until 1946. In 1945, Mahlon P. Etheredge joined the faculty, and the next year, Pelipetz departed and was replaced by Henry V. Allen Jr. Allen remained on the faculty for only two years. During these early years, the curriculum underwent significant modifications with courses commonly found in present-day ChE curriculums being added.

In 1948, Etheredge was named Head of Chemical Engineering. The two-member chemical engineering faculty tradition continued with William A. Reinhardt arriving in 1949 to replace Allen.

In 1952 there was a significant event that continues to impact chemical engineering even today. The state legislature approved funding for a building of 35,602 ft² to house chemical engineering. The building, dedicated in 1956 in honor of Etheredge, continues to be the home of the chemical engineering department today. The faculty grew during the next few years, with Arnold J. Gully joining as Associate Professor in 1953, and Ernest E. Bailey, Everard G. Baker, and Dennis Brown coming in as Acting Instructors.

In 1956, chemical engineering was established as a separate department and Charles W. Selheimer took the helm as the second department head. Gully and Baker remained on the faculty with Selheimer. Then in 1959 the department was transferred from the College of Arts and Science to the
School of Engineering, joining the nine established engineering departments. Earl C. Oden joined the department as Associate Professor and Royce B. Luker joined as Assistant Professor in 1960.

John L. Weeks, Jr., was named head of the department in 1962, and David Cornell joined the faculty in that same year. The faculty, consisting of Weeks, Cornell, Oden, Luker, and Baker, was responsible for the department’s successful accreditation in 1964 by the EPCD. Luker left in 1967. Undergraduate enrollment during those early years grew at a steady pace from the first six graduates in 1938 to approximately 15 to 20 graduates per year during the 1960s.

C. Hai Kuo joined the faculty in 1971, and in 1973 Allen G. Wehr, H.A. Koelling, and William B. Hall came to chemical engineering from the newly dissolved Ceramic and Metallurgical Engineering program, bringing considerable expertise in the materials area to chemical engineering. George Lightsey, a ‘65 alumnus, returned to the department to teach in 1976.

Weeks retired as department head in 1982 and Donald O. Hill, a member of the civil engineering faculty, was named Head of Chemical Engineering. His diverse background encompassed traditional chemical engineering, environmental engineering, and considerable industrial experience and he significantly impacted the development of external research programs by departmental faculty. In 1983, Clifford E. George joined the department. Hill, George, and Kuo continue to serve on the faculty today and have been joined in recent years by Hossein Toghiani (1989), Rebecca Besselsen Toghiani (1989), Steven D. Gardner (1991), Charles A. Sparrow (1993), Rudy Rogers (1993), Nancy S. Losure (1994), and Mark E. Zappi (1996). Table 1 lists the current faculty at MSU along with their research interests.

**CHE HALL OF FAME**

Chemical engineering at MSU has prepared many (1438 BS) graduates who represent the embodiment of success through their careers. In 1989, the Chemical Engineering Hall of Fame was chartered to honor a select group of departmental alumni recognized for their career achievements. Charter members include: David Bradford, ‘40 (President and CEO of Allied Chemical Corporation; deceased); C. Glendon Bradley, ‘64 (President of Ciba-Geigy); Gerald W. Cross, ‘72 (President of Rika-Hercules Chemical Company); Earnest W. Deavenport, ‘60 (President of Eastman Chemical Company); Hunter W. Henry, ‘50 (President and CEO of Dow Chemical U.S.; retired); and Dave C. Swalm, ‘55 (President and CEO of Texas Petrochemicals and Texas Olefins; retired).

In 1992, R.L. Pigford (‘38, Professor Emeritus, University of Delaware) was inducted into the Hall of Fame posthumously, and Lawrence A. Adcock (‘59, General Manager of the Louisiana Division of Dow Chemical USA, retired) and Norman R. Young (‘56, Vice President of Texaco Chemical Company, retired) were also inducted.

**THE NEW CHEMICAL ENGINEERING BUILDING**

Construction is underway for a new $18.6-million building, made possible by a generous gift from Dave C. Swalm (‘55) combined with support from the State Legislature. The building will face Lee Hall, the historic structure after which it is patterned. The Institutions of Higher Learning Board of Trustees in Mississippi recently approved the new name for the chemical engineering department, henceforth to be known as the “Dave C. Swalm School of Chemical Engineering.”
^ TABLE 1
Current Faculty and Research Interests at MSU

| Donald O. Hill • Professor and Head of Chemical Engineering (PhD, Alabama, ’72) | Don is a native of Birmingham, Alabama. He worked as a process engineer for the 3M company in Decatur, Alabama, for seven years prior to returning to school to pursue his graduate degrees. His first academic assignment was Professor of Environmental Engineering at MSU. In 1982, Don was named Head of the MSU’s Department of Chemical Engineering. His primary teaching and research interests center on the environment and the application of chemical engineering principles to solve environmental engineering problems. His current research efforts focus on industrial waste/pollution prevention and catalysis. He teaches the freshman design course that provides entering students with the fundamentals of ChE design. |
| --- |
| Clifford E. George • Professor (PhD, Mississippi State, ’85) | Clifford worked in industry for over fifteen years, gaining considerable experience in the areas of new process development and project management. He has worked in various research, development, and production positions with Copolymer Rubber and Chemical Corp., Calumet Industries, and Crosby Chemical Corp., and has been involved in a variety of systems design involving waste utilization and soils remediation. Early work was sponsored by the Tennessee Valley Authority and Energy Corporation to apply radio frequency and microwave heating techniques to industrial drying processes. As work progressed, experimental techniques and equipment were developed that led to investigation of the use of electromagnetic energy as a heating medium for the detoxification of contaminated soils. George has authored more than twenty papers and has made more than sixty technical presentations at meetings and symposiums. |
| C. Hai Kuo • Professor (PhD, University of Houston, ’64) | Hai joined the faculty at MSU in 1970. Prior to his arrival, he was associated with Shell Development Company and the U.S. Environmental Protection Agency. His research interests and experience include process dynamics and simulation, kinetics of vapor and liquid phase reactions, mass transfer and chemical reactions in gas/liquid and solid/liquid systems, multiphase fluid flow and heat transfer through porous media, and air and water pollution control. |
| Rudy Rogers • (PhD, University of Alabama, ’68) | Before joining the MSU faculty, Rudy worked in industry for eleven years on projects that included non-Newtonian flow of slurries, freeze drying, and small particle phenomena. One area of his research has involved the production of methane adsorbed on coal, and his textbook on the subject, Coalbed Methane: Principles and Practice, was published by Prentice-Hall in 1994. His current research interests focus on gas hydrates. In recent years, gas hydrates (which form abundantly in arctic regions and in deep ocean sediments) have been found to store very large amounts of natural gas. Research at MSU is determining the feasibility of practical uses of natural gas storage in gas hydrates for such applications as peak loads for electric power plants and as an alternative fuel for automotive vehicles. Projects are funded by DOE and Chevron in these and related gas-hydrate topics. Rudy and MSU hold a patent regarding the application. Rudy teaches the mass and energy balances course as well as process design and plant design courses in the ChE department. |
| Charles A. Sparrow • Professor (PhD, Georgia Institute of Technology, ’77) | Charles has been a faculty member at MSU since 1976. His initial appointment was in the Department of Nuclear Engineering. He specializes in computational methods for transport problems, including diffusion theory. Among his interests is the development of methods for detection of small amounts of pollutants in the atmosphere. On the MSU campus, he is associated with the Center for International Security and Strategic Studies, where he organizes symposia to discuss problems associated with disposition of excess fissile materials. His research includes both numerical studies and laboratory measurements. |
| Steven D. Gardner • Associate Professor (PhD, University of Florida, ’90) | Steven’s primary research and teaching interests revolve around the chemical and physical phenomena associated with interfaces. In fact, much of his previous research has been directed toward characterizing diffusion and reaction processes occurring at solid/solid, solid/liquid, and solid/gas boundaries. As a result, he has developed considerable expertise in surface and interface analysis using techniques such as X-ray photoelectron spectroscopy, Auger electron spectroscopy, and ion scattering spectroscopy. He currently directs a surface-analysis laboratory that addresses fundamental research in the areas of heterogeneous catalysis, adhesion (with emphasis on carbon fibers and polymers), and semiconductor gas sensors. Typical activities have included (1) optimizing catalyst compositions for improved yield and selectivity, (2) designing surface treatments for carbon fibers in order to achieve improved adhesion to polymers, and (3) correlating surface composition and surface conductivity of metal oxides as a function of the ambient gas-phase composition. |
| Hossein Toghiyan • Associate Professor (PhD, University of Missouri-Columbia, ’88) | “Dr. H.” (as he is known around the department) was born in Isfahan, Iran, and teaches the senior-level process control course. He also often teaches the reactor design and unit operations laboratory courses as well as graduate courses. He has worked with DIAL in the area of process gas analysis and is a major team player in the control efforts currently underway within DIAL. He also maintains research activities in the areas of polymer composites and phase equilibria. In collaboration with Dr. Hill, he is investigating the production of alcohols from synthesis gas derived from a variety of waste materials found throughout the state, including sawdust. |
| Rebecca K. Besselsen Toghiyan • Associate Professor (PhD, University of Missouri-Columbia, ’88) | “Dr. R.” (as he is known around the department) was born in Isfahan, Iran, and teaches the senior-level process control course. He also often teaches the reactor design and unit operations laboratory courses as well as graduate courses. He has worked with DIAL in the area of process gas analysis and is a major team player in the control efforts currently underway within DIAL. He also maintains research activities in the areas of polymer composites and phase equilibria. In collaboration with Dr. Hill, he is investigating the production of alcohols from synthesis gas derived from a variety of waste materials found throughout the state, including sawdust. |
| Nancy S. Loste • Assistant Professor (PhD, Michigan State University, ’94) | After receiving her BS degree, Nancy accepted an entry-level engineering position at Dow Chemical and carried out various assignments in polymer research and production plants, culminating with four years in the Styrene/Butadiene Latex production plant as a production engineer. In 1987 she resigned from Dow to pursue graduate study at Michigan State University. Since coming to MSU in 1994, she has pursued projects in polymer recycling and composite material production methods (notably in reaction injection molding) and Kenaf/polymer blends. Her industrial experience has also been put to use in service of MISSTAP, where she conducts waste elimination and pollution prevention audits of Mississippi industries. She teaches polymer and materials science courses and the unit operations laboratory course. |
The ground-breaking ceremony included Dave C. Swalm, Governor Kirk Fordice, President Donald Zacharias, College of Engineering Dean A. Wayne Bennett, and a host of alumni and friends of chemical engineering. The new 95,000 ft² building will feature state-of-the-art multimedia technology in the classrooms and will significantly expand the department’s research and teaching facilities. The first two floors of the five-story red brick structure will include classrooms for general university use and a 140-seat auditorium. The upper floors will house chemical engineering classrooms, laboratories, and offices. Construction will be completed in 1999.

TODAY’S UNDERGRADUATE PROGRAM

The undergraduate program features the common core of science, engineering, and mathematics courses combined with traditional chemical engineering offerings. Electives drawing on faculty research expertise provide students with an opportunity to broaden their undergraduate academic experience in membrane separation processes, pollution abatement and remediation, air pollution control, hazardous waste incineration, experimental methods in materials research, and high polymer theory. The undergraduate program is accredited by ABET, requires 138 semester credit hours (see Table 2), and currently has 320 students. Departmental enrollment of women and minorities is highest in the College of Engineering, with 103 women and 82 minority students currently enrolled. The entering freshman class to the chemical engineering program always makes its presence known by having the highest average ACT score of any department in the College of Engineering.

The undergraduate curriculum has recently undergone significant modifications that allow students to focus elective courses in an area of interest to them. Other major modifications to the four-year BS-degree program include the addition of a seminar (1 hour) and a design-concepts course (3 hours) in the freshman year as well as more even distribution of the required ChE courses over the sophomore through senior years.

Undergraduates enjoy an excellent unit-operations laboratory experience made possible through the generosity of the Dow Chemical Company, Eastman Chemical Company, and the hard work of the Drs. Toghiani and Dr. Hill. Funding in the amount of $250,000 from Dow and $118,000 from Eastman allowed the design, construction, and integration of equipment for over eighteen new experiments to be added to the laboratory between 1989 and 1993. These experiments cover the spectrum from traditional unit operations to emerging technologies. Much of the equipment was built in-house and was designed to demonstrate textbook principles. Integration of the equipment with an industrial-style control system provides the undergraduates with a solid laboratory experience.

| TABLE 2 |
| Chemical Engineering Curriculum at MSU |

<table>
<thead>
<tr>
<th>FRESHMAN YEAR</th>
<th>Second Semester</th>
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<tbody>
<tr>
<td>First Semester</td>
<td>Second Semester</td>
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<tr>
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<td>Fund. of Chemistry I</td>
<td>Fund. of Chemistry II</td>
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<tr>
<td>ChE Freshman Seminar</td>
<td>Design Concepts for ChE</td>
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<td>English Comp. II</td>
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<tr>
<td>Calculus I</td>
<td>Calculus II</td>
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<tr>
<td>Fund. of Public Speaking</td>
<td>Physics I</td>
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<td>Social Science Elective</td>
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<td>Second Semester</td>
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<tr>
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<td>Calculus IV</td>
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<tr>
<td>Physics II</td>
<td>Physics III</td>
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<tr>
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<td>ChE Thermo I</td>
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<tr>
<td>Fluid Flow Operations</td>
<td>Heat Transfer Operations</td>
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<tr>
<td>Fine Arts Elective</td>
<td>Differential Equations</td>
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<tr>
<td>Social Science Elective</td>
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<th>JUNIOR YEAR</th>
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<tr>
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<td>Organic Chem. Lab II</td>
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<td>Organic Chemistry I</td>
<td>Organic Chemistry II</td>
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<tr>
<td>ChE Thermo II</td>
<td>Mass Transfer Operations</td>
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<tr>
<td>Analysis &amp; Simulation</td>
<td>Chem. Reactor Design</td>
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<td>ChE Lab I</td>
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<tr>
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<td>Engineering Materials</td>
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<td>HU/FA/SS Elective</td>
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<td>Second Semester</td>
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<td>Physical Chem. Lab</td>
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<td>Technical Elective</td>
<td>Technical Elective</td>
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<tr>
<td>Total Credit Hours</td>
<td>Total Credit Hours</td>
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The ChE department is a strong proponent of cooperative education, and over 40% of our undergraduates participate in the program. Students in the program rotate three (or more) work semesters with school semesters. Most students begin their co-op rotation in the second semester of the sophomore year. The reorganization of the ChE curriculum provides them with classroom exposure to more ChE concepts as they move through the co-op sequence. To accommodate the various work/school rotations, the department offers all but two of the undergraduate required courses each fall and spring semester and also offers a number of key prerequisite courses during the summer session.
THE GRADUATE PROGRAM

The department offers two programs of study at the MS level. Students pursuing the traditional chemical engineering option complete a set of four core graduate courses encompassing the topics of transport phenomena, thermodynamics, chemical reaction kinetics, and process computations. The core graduate courses are offered on a three/four semester rotation. Six semester credit hours in advanced mathematics are required, as are six hours of technical electives for the MS in chemical engineering. In addition, candidates from other fields of study (chemistry or another engineering discipline) can pursue the MS in chemical engineering after they have completed a select set of undergraduate prerequisite courses.

Students pursuing the industrial hazardous-waste-management option complete 24 hours of graduate courses that are selected to provide them with depth and breadth in the areas of environmental engineering and hazardous/industrial waste treatment/remediation technology. This option is available only to those who enter the graduate program with an undergraduate degree from an accredited engineering program. Successful completion of either MS degree program requires the submission and defense of a thesis by the candidate.

The ChE department participates in an interdisciplinary PhD program leading to the PhD in Engineering. The program requires 24 hours of graduate course work in addition to the MS requirements and a minimum of 20 hours of dissertation research. Students must also complete a qualifying examination, a preliminary/comprehensive examination and submit and defend a PhD dissertation.

Students can pursue a graduate degree through the off-campus graduate program. A number of recent graduates from the program have pursued their MS degrees while working in industry. Because of its moderate size, graduate classes of approximately ten students are common, providing for close association between the graduate students and their teachers and research advisors. Students interested in pursuing a graduate degree at MSU are encouraged to contact the department. Faculty research activity is growing steadily, and we are always seeking qualified students for our graduate programs.

RESEARCH FACILITIES

Since 1989, the department has experienced significant growth in research. Energy and the environment continue to be strong areas of research interest within the department. George, Sparrow, H. Toghiani, and R. Toghiani collaborate with DIAL, while Gardner and Losure are actively involved in the Materials Research Group within the College of Engineering.

The Mississippi Technical Assistance Program (MISSTAP) was established in 1989 through a grant from the Mississippi Department of Environmental Quality. It is a non-regulatory, client-confidential, technical-assistance program designed to assist Mississippi industries, businesses, and communities in identifying pollution prevention (P2) solutions for both their RCRA waste and their conventional waste. On-site technical assistance, waste assessments, and compliance monitoring are provided at no charge to industry. MISSTAP personnel are available to provide assistance as an informational clearinghouse and through a library devoted to P2 and the environment. The library and a hotline to the Waste Reduction Resource Center in Raleigh, North Carolina, provide the basis for fast and efficient technology-transfer activities. Research and development activities are carried out confidentially, but require a funding source.

The Environmental Technology Research and Applications Laboratory (E-TECH Laboratory) is the newest research laboratory established in the department. Its mission is to support government and industry through the development and application of pollution treatment and abatement techniques that provide cost-effective treatment of the environment. Mark Zappi serves as its director, and Hill, Kuo, and George contribute in research endeavors.

THE COMING YEARS

The past decade has been one of tremendous growth and change for the department. We are excited about all of the opportunities that we will be part of over the coming years. Our new building is set for completion during 1999 and our current freshman class will be among the first to fully utilize the facility. We anticipate growth of our graduate programs and our research endeavors in the years to come. Mississippi State is a great place to pursue chemical engineering studies, and Starkville is a great place to live. Y’all come down and see us, y’hear?

ACKNOWLEDGMENT

Photos are courtesy of Fred Faulk, University Relations, Mississippi State University.
Ronald W. Rousseau
of Georgia Tech

Amyn S. Teja
Georgia Institute of Technology • Atlanta, GA 30332-0100

Coauthor of the best-selling textbook in the history of chemical engineering... outstanding teacher and researcher... chair of one of the largest chemical engineering departments in the nation... AIChE director... chair of the Council for Chemical Research... scholar-athlete... baseball player and fan—these are only some of the landmarks along the way that delineate the life and career of Ronald W. Rousseau of the North Avenue Trade School (Georgia Tech).

Ron was born in Bogalusa, Louisiana, and spent the early part of his life in Baton Rouge. He recalls selling 7-Ups at Louisiana State University football games during those early years and never had “any thought of going to college anywhere other than LSU.” While he was at LSU, he was awarded an athletic scholarship and lettered three years in varsity baseball. He says he “did not start out as a great student,” and confesses it was partly because he had visions of playing professional baseball. But he found his niche after getting the highest grade in a stoichiometry course taught by Dave Greenberg. From that time on, baseball played second fiddle to chemical engineering—a trend that has continued to this day.

During Ron’s senior year, Jesse Coates (who was department head at LSU at that time) talked about the possibility of graduate school if Ron continued to do well in his chemical engineering classes. As a result of his encouragement, Ron eventually obtained both his BS and PhD degrees at LSU, the former in January of 1966 and the latter in May of 1969. His PhD...
[Ron] says he
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research was concerned with reacting cellulose to produce ion exchange resins and was directed jointly by Clayton Callihan and Bill Daly. Ron reminisces that Callihan had “unbridled imagination and industrial experience,” whereas Daly had “the rigor and enthusiasm for pure research.” Both these men, and several others (including Paul Murrill, Dave Greenberg, and Frank Groves) were great influences on Ron’s subsequent career as a professor.

TEACHING AND RESEARCH

After obtaining his PhD, Ron accepted a position as Assistant Professor at North Carolina State University. He remained there for seventeen years, rising through the ranks to become Professor of Chemical Engineering in 1980. He formed many associations during these years in Raleigh, the most notable of which were his collaborations with Warren McCabe, Rich Felder, and Jim Ferrell.

Warren McCabe spent what he called his “Indian Summer” at NC State and was instrumental in Ron’s entry into the field of crystallization. Together, Warren and Ron did pioneering work on contact nucleation and identified mechanisms by which anomalous crystal growth occurs. This led to Ron’s later work on the role of nucleation and growth in determining crystal habit, purity, and size distributions. It also led to over 135 publications and an equal number of presentations, as well as to his current research on the use of crystallization technology in the separation and purification of specialty chemicals.

Ron’s research in crystallization as a separation technology naturally led to an interest in other separation processes and to the giving of more than 150 short courses that emphasized crystallization, distillation, extraction, and general separation. Ron also edited The Handbook of Separation Process Technology (Wiley, 1987), which has become a standard reference on separations for the profession.

All this body of work culminated in the Clarence G. Gerhold Award of the American Institute of Chemical Engineers in 1996. This award is given by the Separations Division of AIChE for “a notable record of outstanding contributions to separations teaching and research.”

Another association, formed during his years at NC State, was with Rich Felder. Together they coauthored Elementary Principles of Chemical Processes (Wiley, 1978 and 1986), which is the most widely used chemical engineering textbook in the world. It is used by more than 80% of the chemical engineering programs in the United States and has sold over 110,000 copies worldwide. Felder and Rousseau brought “a perfect blend of styles and interests” to the writing of this book—Ron brought broad concepts and case studies, while Rich brought specific
topics, computational techniques, and the communication style. According to Ron, the book has been successful "beyond my dreams." He is working on the third edition at the present time.

A third association formed at NC State was with Jim Ferrell, who was department head for much of Ron's time there. Although Jim made Ron "teach two courses per semester for seventeen years," he also influenced him on many aspects of administration and eventually convinced him to apply for his present position as Chairman at Georgia Tech.

He accepted the chairmanship position "much to the chagrin of my wife, Sandra," he says.

**ADMINISTRATION AND SERVICE**

His timing in accepting the chairmanship at Georgia Tech, of course, was perfect. Its School of Chemical Engineering had made tremendous strides under Gary Poehlein's leadership; Gary had hired fifteen new faculty and had brought the school's undergraduate and graduate programs into national prominence. Enrollments were still increasing when Ron took over, and he found a very supportive dean in Bill...
Sangster when he set out to address the problems created by increasing numbers of students. Ron has hired some outstanding new young faculty (Sue Ann Bidstrup-Allen, Pete Ludovice, Jeff Morris, Mark Prausnitz, Matthew Realff, Mary Rezac, Thanassis Sambanis, Tim Wick) and some outstanding senior faculty (Chuck Eckert, Dennis Hess, Paul Kohl, Arnold Stancell). Two of the young faculty are Presidential Young Investigators, and two of the senior faculty are members of the National Academy of Engineering. Indeed, with a supportive administration behind him, the School of Chemical Engineering has been “in a hiring mode” for both junior and senior faculty ever since 1977. The faculty now numbers 32 and “we are still planning to add more,” says Ron.

Ron has also seen the number of students grow to the present 800 undergraduates, 120 graduate students, and a dozen or so postdoctoral associates, and staff members now number 14. Faculty members have also been active participants in several interdisciplinary programs, including bioengineering, polymers, microelectronics, pulp and paper, specialty separations, and manufacturing.

As an educator and a researcher, Ron has enjoyed the success and achievements of the forty-or-so Masters and Doctoral students whose theses he has supervised. His crop of advisees include Bob Kelly and Clifford Tai (currently on the faculty at NC State and National Taiwan University, respectively) as well as Jim Boone, Russ O’Dell, Te Chang, Ron Zumstein, and Ray Harrison, who went on to stellar careers at Ethyl (now Albermarle), Hoechst, Arco, and Weyerhaeuser, respectively. Ron continues to advise graduate students and to delight in their achievements.

Ron’s service activities attest to his love for the chemical engineering profession. He has organized and chaired numerous symposia at national and international conferences on separations. He was the 1995 co-chair of the Separations Foundation Conference on separations, was a founding director of the Separations Division of AIChE, and has served as a consulting editor of the AIChE Journal, as associate editor of the Journal of Crystal Growth, and as a member of the editorial advisory boards of Separations Technology and Chemical Engineering Education.

As a director of AIChE in 1990-93, Ron was able to see what people outside academia and outside the profession could contribute to chemical engineering education. His services continue to be in demand, as he is currently a member of the task force for restructuring AIChE in order to relate more effectively to its 55,000 members.

Ron also serves as the current chair of the Council for Chemical Research (CCR), an organization consisting of heads of all PhD-granting chemistry and chemical engineer-
ASEE ANNUAL CONFERENCE
Seattle, Washington
June 28 - July 1, 1998

REGULAR SESSIONS

Session 1213 • Getting Faculty Buy-In to Good Teaching
- Faculty Development: Getting the Sermon beyond the Choir
- Changing the Culture: What’s at the Center of Engineering Education
- Re-Engineering Faculty Development: Lessons LEA/RNed

Session 1313 • Breathing Life into Traditional Courses
- A Traditional Material Balances Course Sprinkled with Non-traditional Experiences
- Chemical Engineering Thermodynamics – Transforming ‘Thermo’ Lectures into a ‘Dynamic’ Experience for Undergraduates
- Bringing Active Learning into the Traditional Classroom: Teaching Process Control the Right Way
- A Tournament to Exercise Process Economics Concepts
- A Project-Based, Spiral Curriculum for Chemical Engineering

Session 1413 • Computer Survey-Training for ChE Profession
- Results of a recent CACHE survey of Computer Usage
- Panel Discussion of Ramifications for Curriculum Implications with Academic and Industrial Participants

Session 1513 • Fitting the Essential Extras in the ChE Curriculum
- Jump-Starting Life-Long Learning
- Fitting the Essentials into the ChE Curriculum: Ethics, Professionalism, Environmental Health & Safety
- Leadership and Mentoring in Undergraduate Engineering Programs
- Integrating Process Safety into the Unit Operations Laboratory
- Applied Chemical Process Statistics: Bringing Industrial Data to the Classroom
- An Industrial Approach to the Unit Operations Laboratory Course

Session 2413 • Experimental Education in ChE
- If You Let Them Build It, They Will Come”: Hands-on Projects for Freshman to Enhance Student Learning and Interest
- A Multidisciplinary Electrochemical Engineering Laboratory Course
- Structured Cooperative Learning in the Undergraduate Chemical Engineering Laboratory
- Implementing a Computer Laboratory
- Chemical Engineering Principles in a Freshman Engineering Course using a Cogeneration Facility

Session 2513 • Outcomes Assessment I: Is a “C” Good Enough?
- Assessment for Improvement: Coming Full Cycle
- Assessment Process at a Large Institution
- Assessment for Improvement in the Classroom
- Feedback Loops in Large Service Courses
- Implementing an Integrated System for Program Assessment and Improvement
- Panel Discussion

Session 2613 • Outcomes Assessment II: Is a “C” Good Enough?
- Closing the Assessment Loop
- Electronic Portfolios: What to Do with the Information
- Using a Faculty-Generated Matrix to Close the Assessment Loop
- Lessons Learned from a Decade of Assessment
- An EC2000 Visit: Perspectives from Both Sides of the Fence
- Panel Discussion

Session 3213 • Academic Advising Issues
- Recruiting and Advising of High School Students from “Non-Traditional” Groups
- Enhancing Under-represented Student Opportunities Through Faculty Mentoring and Peer Interactions
- A Department-Wide Distributed Advising System
- Issues Important to the Advising of Student Chapters of Professional Societies
- Career Choices for Chemical Engineering Students
- Is Grad School for Me?

Session 3413 • Pollution Prevention/WERC Design Contest
- Design Contest: Pollution Prevention by Design and
Capstone Design Course

- Government, Industry and Academia: An Effective Partnership to Address Real Environmental Challenges
- An Alumni Survey as an Assessment Tool for New Mexico Tech’s BS Environmental Engineering Curriculum
- Subterranean Spout Bed Technology for Removal of Contaminants from Groundwater
- Remediation of Radionuclide-Contaminated Aquifer
- Importance of Chemical Reactivity in Understanding Environmental Hazard
- Chemical Processes in Environmental Engineering

Session 3513 • Innovative Uses of Computers in ChE

- Interactive Web Site for Teaching Chemical Reaction Stoichiometry
- A World Wide Web Based Textbook on Molecular Simulation
- Novel Uses of the World Wide Web to Manage an Undergraduate Process Control Course
- Web Lab: Running Laboratory Experiments via the World Wide Web
- Multimedia Encyclopedia of Chemical Engineering

Session 3613 • Effective Use of Process Simulators

- A Novel Use of HYSIS to Design an Industrial Refrigeration System
- Process Simulation in ChE Design: A Potential Impediment to, Instead of a Catalyst for, Meeting Course Objectives
- Experiences Using MATLAB/Simulink for Dynamic “Real-Time” Process Simulation in an Undergraduate Process Control Course
- Teaching ChE Principles by Use of Sophisticated Process Design Software to Design a Ketchup Manufacturing Process
- Integration of AspenPlus (and other Computer tools) into the Undergraduate Chemical Engineering Curriculum
- Coordinating Equilibrium-based and Rate-based Separations Courses with the Senior Process Design Course

OTHER SESSIONS

Session 1113 • ChE Div. Executive Committee Meeting

Session 1613 • Chemical Engineering Division Meeting /Lectureship Presentation

The Chemical Engineering Division will have a short business meeting that will be immediately followed by the Division Lectureship presentation

Session 1713 • ChE Division Reception/Mixer Sponsored by the CACHE Corporation - Monday Evening

This reception will be provided to the members of the Chemical Engineering Division for a chance to socialize and to honor the Division Lectureship Award winner

Session 2713 • Chemical Engineering Division Dinner-Tuesday Evening

The ChE Department at the University of Washington will host an optional pre-dinner visit that will include a wine and cheese poster session of department activities and research

All chemical engineering division members and guests are invited to attend the annual Chemical Engineering Division Dinner at the Faculty Club on the University of Washington campus. Winners of the ChED awards will be recognized, and an entertaining non-technical presentation will be made.

Session 3113 • ChE Chairpersons Breakfast

ABET 2000 - What curriculum changes are being planned because of new procedures (e.g. Chemistry, design, PE exams, etc.)?

Discussion: Graduate’s Employment, 1998

Discussion: Industry Participation in Design

Check out the 1998 ASEE Annual Conference & Exposition Information at http://www.asee.org/conferences/html/annual_98.htm

Spring 1998
We extend our appreciation to Robert Davis (University of Colorado) for acting as Guest Editor in compiling, reviewing, and editing the following seven papers that comprise a special-feature section on particle science and technology in this issue.

TEACHING FLUID-PARTICLE PROCESSES
A Workshop Report

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Many chemical engineering departments are in the process of revising their curricula, due, in part, to the increased flexibility associated with new criteria approved by the Accreditation Board for Engineering and Technology (ABET) and to input received from alumni and industry. One area that is being considered is fluid-particle technology.

Chemical engineering products in particulate form, or with particulate additives, include pharmaceuticals, paints, fertilizers, ceramics, detergents, juices, magnetic and photographic films, cosmetics, processed foods, etc. Indeed, it has been estimated that more than half of the products of the major U.S. chemical companies are solids.\textsuperscript{[1]} Still, our courses tend to focus on fluids (gas or liquid) rather than on solids transport, on molecular rather than particulate separations, and on single-phase or homogeneous rather than multiphase or heterogeneous reactions. Several recent articles report on studies that contrast significant educational programs on particle technology in Canada, Europe, and Japan with the relative neglect of this subject in the United States.\textsuperscript{[1,4]}

Although the need to train chemical engineers in basic particle technologies commonly encountered in industry is becoming more widely recognized, there remains a lag in the development and use of appropriate teaching materials. In light of this, we were asked to arrange a series of workshops on teaching fluid-particle processes for the ASEE Summer School for Chemical Engineering, held in August of 1997 in Snowbird, Utah. The purpose of these workshops was to exchange experiences on fluid-particle educational efforts and to identify existing and proposed materials and approaches that may assist others in the future.

In this article, we summarize the findings and recommendations of the workshop participants. Further details on demonstrations, experiments, simulations, modules, and courses that may be used to help teach fluid-particle processes are given in the companion articles in this journal issue\textsuperscript{[6-11]} as well as in related articles from past issues.\textsuperscript{[12-18]}

OVERVIEW OF WORKSHOP CONTENTS

A list of the three half-day workshops is given in Table 1. The four keynote overviews, two from industry and two from academia, presented broad views of the need for teaching fluid-particle processes and of recent progress to address this need in U.S. chemical engineering curricula. Additional presentations were made on individual courses, lab exercises, simulations, and demonstrations on fluid-particle processes. There was strong audience participation during the discussions that followed each presentation and via breakout groups on the development of teaching materials.

In their keynote presentations, Ralph Nelson (DuPont), Bob Pfeffer (New Jersey Institute of Technology), Ted Knowlton (Particulate Solids Research), and Frank Tiller (University of Houston) noted that the "legacy of neglect"\textsuperscript{[2]}

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Liang-Shih Fan is Distinguished University Professor and Chair of Chemical Engineering at the Ohio State University. He received his BS degree from the National Taiwan University, his MSChE and PhD degrees from West Virginia University, and an MS in Statistics from Kansas State University. His research and teaching interests are in fluidization and multiphase flow, powder technology, and particulates and multiphase reaction engineering.

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Chemical Engineering Education
of particle technology in U.S. education is beginning to change.\[6,7\] Industry-backed professional societies such as the American Filtration and Separations Society (AFS) and the Particle Technology Forum (PTF) of the American Institute of Chemical Engineers (AIChE) have formed educational committees to promote the development of textbooks, short courses, and other educational tools for particle technology. The Fluid, Particulate, and Hydraulic Systems Program of the National Science Foundation (NSF) has supported several educational projects in this area. Research centers, such as the Engineering Research Center for Particle Science and Technology at the University of Florida, the Particulate Materials Center at Pennsylvania State University, the Particle Technology Center at the New Jersey Institute of Technology, and the Ohio Board of Regents Consortium on Fine Particle Technologies, led by the Ohio State University, also have significant educational components.

Current educational approaches for teaching particle science and technology in chemical engineering curricula fall into three categories:

- **Multicourse sequences or options**
- **Single elective courses**
- **Modules and exercises in standard courses**

Examples of each of these modes were included in the workshop presentations.

U.S. schools (including the City College of the City University of New York, the University of Cincinnati, the University of Florida, New Jersey Institute of Technology, Ohio State University, and Pennsylvania State University) now offer or are planning multiple elective courses on particle science and technology.\[^7,11,13\] They include a mix of undergraduate and graduate courses and cover topics such as basic particulate mechanics, particle formation, particle characterization, sedimentation, gas and liquid fluidization, filtration, conveying, mixing, cyclones, and hoppers. Due to the interdisciplinary nature of the subject matter, the course offerings are often cooperative efforts of chemical, civil, and mechanical engineering departments.

Several additional U.S. chemical engineering departments offer single elective courses in particle-related subjects such as colloids, fluidization, particle formation, powder technology, fluid-solid flow, particle processing, and suspension mechanics. Example courses were presented in the workshops by Tony Rosato,\[^7\] Gabriel Tardos,\[^13\] Sotiris Pratsinis, Rob Davis,\[^12\] Karl Jacob,\[^10\] and L.-S. Fan. Many of the elective courses are aligned with the research interests of the instructors and draw relatively small numbers of graduate students and advanced undergraduates. Karl Jacob described a unique undergraduate course on the basics of solids processing, which he taught at the University of Akron.\[^10\]

In contrast to the examples cited above, most U.S. chemical engineering departments do not currently offer a course in particle science and technology.\[^5\] Even so, fluid-particle processes may be introduced in any chemical engineering curriculum by incorporating appropriate modules and exercises in standard courses such as materials and energy balances, transport phenomena, separations, reaction engineering, design, and the unit operations laboratory. During the workshops, Jennifer Sinclair (Purdue) showed how simulation packages can be used to illustrate fluid-particle flows\[^8\] and George Klinzing (University of Pittsburgh) described several simple demonstrations and laboratory exercises on powder flow.\[^9\] In addition, the Engineering Research Center for Particle Science and Technology at the University of

### TABLE 1

**Workshops on Fluid-Particle Processes**

| WORKSHOP #1 |
| Keynote Overviews |
| ・ Ralph Nelson and Reg Davies, DuPont |
| ・ Industrial Perspective on Teaching Fluid-Particle Technology in Chemical Engineering Curricula |
| ・ Bob Pfeffer, New Jersey Institute of Technology |
| ・ Particle Technology in the Engineering Curriculum—Can We Make it Happen? |
| Case Studies, Design Projects, and Experiments |
| ・ Tony Rosato, New Jersey Institute of Technology |
| ・ Particle Technology Research-Based Curriculum Development: A Case Study |
| ・ Jennifer Sinclair, University of Arizona |
| ・ Case Studies in Fluid-Particle Flow Using CFD |
| ・ George Klinzing, University of Pittsburgh |
| ・ Pneumatic Conveying: Design, Demonstrations, and Lab Exercises |

| WORKSHOP #2 |
| Keynote Overview |
| ・ Ted Knowlton, Particulate Solids Research |
| ・ Particle Technology in Industry and the Need for Curricula on Fluid-Particle Technology in Chemical Engineering |
| Courses on Fluid-Particle Processes |
| ・ Gabriel Tardos, City College of the City Univ. of New York |
| ・ Teaching about Powders and Powder Technology to Chemical Engineering Students |
| ・ Sotiris Pratsinis, University of Cincinnati |
| ・ Particulate Formation Processes |
| ・ Rob Davis, University of Colorado |
| ・ Suspensions and Colloids |

| WORKSHOP #3 |
| Keynote Overview |
| ・ Frank Tiller, University of Houston |
| ・ Short Courses on Fluid/Particle Processing and Separation, Intercalibration, and Particle Science |
| Courses on Fluid-Particle Processes |
| ・ Karl Jacob, Dow Chemical/George Chase, Univ. of Akron |
| ・ Undergraduate Teaching in Solids Processing/Particle Technology: An Academic/Industrial Approach |
| ・ L.-S. Fan, The Ohio State University |
| ・ Teaching Gas-Solid Flows from a Particle Technology Perspective |

Reports by Breakout Groups on Development of Course Materials Wrap-Up Discussion and Plans
Particle Science and Technology

Florida is developing several ready-to-use instructional modules that are, or soon will be, available for general use.[11]

At the end of the second workshop, the participants were divided into four breakout groups, based on their interests and expertise, covering topics such as solid-liquid systems (colloids and suspensions), solid-gas systems (powder mechanics and flow), computer simulations of fluid-particle systems, and particle processes (formation, growth, size reduction, and characterization). Each group was given the following charge:

- List current impediments to the teaching of particle technology
- Propose possible solutions to these impediments
- Suggest specific examples of materials that can be used to help teach particle technology
- Present group findings during the third workshop

The findings of these breakout groups, as well as the recommendations made during the ensuing discussion, are summarized in the following section.

SUMMARY OF RECOMMENDATIONS

The different working groups had remarkably similar findings; they are grouped together and summarized in Table 2. First, there is a need for increased awareness of the importance of fluid-particle processes in the various industries that employ chemical engineers. Students in particular need to be shown the value of training in this area through field trips, presentations, written materials, and hands-on experience. Faculty and administrators must also be convinced if significant curricular change is to be effected. Industry and professional groups will need to continue to play a lead role in this regard.

Second, it is difficult to introduce new subjects in the chemical engineering curriculum, which at most universities is already quite full and considered one of the broadest, deepest, and most difficult majors. Moreover, particle technology to many lacks the glamour or attention associated with subjects such as biotechnology, environmental engineering, and microelectronics processing, which are all competing for space. Fortunately, the diverse nature of fluid-particle processes allows for great flexibility in how the subject is addressed. As noted previously, departments may introduce modules, examples, and experiments in existing courses, develop a full course on fluid-particle processes, or offer a special option in particle technology. The last may be particularly attractive for a combined BS/MS degree. The workshop participants recommended that all chemical engineering departments include training in fluid-particle or particulate multiphase processes in some way in their curricula.

Perhaps the greatest impediment to teaching particle technology is the lack of available materials that cover, to a great extent, the relevant interdisciplinary topics. The workshop speakers noted that since there are no suitable textbooks for the courses, they used a reserve list of several reference books and specialty texts that are relevant to various portions of the courses (a partial list of these books is included in the reference section of this article[19-39]). To help remedy this situation, Frank Tiller reported that the American Filtration and Separations Society is developing four texts covering particulate and interfacial science engineering, flow through porous media, fluid-particle mechanics, and fluid-particle separations. We strongly urge that any new texts contain a liberal amount of homework and example problems that can also be used in traditional chemical engineering courses. In addition, there is a need to create other teaching materials, such as software, CD-ROMs, short teaching modules, demonstrations, laboratory experiments, and example courses. A partial list of published materials is included with this article,[7-18] but since many of the materials created by individual faculty are unpublished, it was recommended that a website be created as a resource for such materials.

Finally, the workshop breakout groups all noted that the lack of trained faculty has impeded the inclusion of fluid-
particle processes in chemical engineering curricula. This problem is easily solved. Besides the obvious (though not always easy) approach of hiring new faculty with suitable expertise, there are short courses available to train faculty as well as industry employees. Further, courses can be offered to students by experienced industry representatives or faculty from other campuses through long-distance learning media. In his keynote presentation, Frank Tiller reported on four recent workshops with grants for faculty participation from NSF’s Undergraduate Faculty Enhancement Program. Moreover, we believe that most chemical engineering faculty members will be able to include fluid-particle or multiphase processes in their courses once the suitable teaching materials are developed and made available.

WHERE DO WE GO FROM HERE?

Three specific actions have been undertaken as a result of the workshop recommendations:

- This collection of articles in CEE is being published to communicate how fluid-particle processes are being taught in several universities and to provide resource materials for others.
- A website has been initiated for archiving and distributing additional educational materials on particle technology. Ralph Nelson has taken the lead on developing this website, and further information is available in his article with Reg Davies. (6)
- A formal request was made to the Education and Accreditation Committee of AIChE to include particulate and multiphase processes in the new CHE ABET criteria, with departments given flexibility on how they provide training in this area.

In the process of reviewing their curricula, we urge all chemical engineering departments to consider how to more fully include particulate and multiphase processes. In addition, we hope that others will make educational materials on particle technology available through publications, presentations, the world-wide web, and software distributors.

REFERENCES

INDUSTRIAL PERSPECTIVE ON TEACHING PARTICLE TECHNOLOGY

RALPH D. NELSON, JR., REG DAVIES
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Particle technology (PT) deals with such problems as powder flow, cohesion, adhesion, surface reactions, rheology, segregation, and fouling. Industry wants

- Technical graduates who have some knowledge of PT
- Institutions to provide career-long training in PT
- External consulting and analytical resources
- Consortia to find answers for common design and operation problems
- Managers who recognize the importance of PT

Three sectors must cooperate to accomplish this goal: industry, government, and academia. Academia provides most of the formal training, while government funds education in critical-but-undeveloped areas. Industry supports apprentice programs, external continuing-education courses, and research consortia such as the International Fine Particle Research Institute, the Solids Processing Services, the Engineering Research Center for Particle Technology (University of Florida), the Center for Advanced Materials Processing (Clarkson University), and the Particulate Materials Research Center (Pennsylvania State University). How are the Nations that have Strong PT Positions Faring at this Point?

Japan’s PT community is well organized and innovative, with an extensive industrial base and strong academic programs. For twenty-five years their APPIE organization has provided a strong informational base and a cohesive link between industry, university, and government. They support the East Asian professors of PT who hope to coordinate academic development of PT in Japan, China, Korea, Thailand, Singapore, and Taiwan. The Hosakawa Corporation has acquired manufacturing plants in several countries, perhaps becoming the world’s largest supplier of fine (dry) particle mills, mixers, classifiers, etc., and is a strong partner in academic research and consortia. Several observers, however, say that Japan’s extensive support for research overseas may have caused research at home to suffer.

In Germany, Rumpf’s leadership in PT during the 1950s created a strong industrial and academic base. Both German and U.S. chemical manufacturers recruit a large fraction of their PT experts from German and other European universities. But Freemantle notes that economic pressures arising from reunification are causing some concern, that the number of PT centers and the duration of university training programs are under scrutiny, and that there has been a significant drop in engineering enrollment at major universities.

England, France, the Netherlands, and Switzerland have active academic centers and industrial centers of PT. A “Specially Promoted Program in PT” focused national attention on PT in England. For a decade it drew together academics from several disciplines to address complex problems. This program has been replaced by the equally successful “Soft Solids” program. The Netherlands has started similar efforts to coordinate research.

Australia, long aware of particle-related problems in the mining and minerals industries, has initiated a National Center for Multiphase Flow, funded through the Australian Research Council.

Russia has a long and strong tradition of technical excellence in PT, but Lepkowski reports that since the breakup of the USSR the physical structure for technology has deteriorated and many faculty have become dependent on consulting income. Long-term industrial stability and the future of the relationship between government, industry, and academia remain questions without answers.

In contrast, the U.S. is now beginning to get its act to-

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Reg Davies is Principal Consultant and Research Manager for the Particle Technology Group at the DuPont Co. and has consulted on industrial processes for over thirty years. He was Technical Director of the International Fine Particle Research Institute for 1979-91 and Chair of the AIChE’s Particle Technology Forum for 1994-96.
Problem and Interdisciplinary Research Center for Particle Technology (ERC-PT) at the University of Florida (and other academic centers of PT), and a newly proposed development—the Particle Process Industries in the Americas (PPIA)—should help us solve PT problems.

What is the Challenge?

Most of the products sold by chemical companies are in particulate form, but the technology for producing and handling particles in commercial processes is rarely taught in the United States. Consequently, although most of the production problems faced by new (or old) chemical technologists are related to particles, few of these technologists have had any formal training to help resolve them. The resulting cycle of guesswork-fail-try again costs U.S. industries millions of dollars a year. If U.S. universities do not help meet the challenge, those nations where technologists have superior training in this area will continue to expand their market share and to acquire U.S. companies, reducing taxes available for U.S. university support and relocating job opportunities to other nations.

Alas, the vast majority of new engineering graduates in the U.S. have no idea of the technologies associated with processes involving particles, the commercial value of PT, what PT problems are easily solved, or what PT problems are difficult to solve and where to get help. In 1992, we listed several factors that make resolution of the challenge difficult:

- The necessary elements of expertise reside in many disciplines, no one of which provides a principal “home” for particle technology.
- Courses are being developed in isolation, and it is hard to add them to an existing curricula or to replace courses that are now in place.
- A multidisciplinary team effort is needed; but it is hard to construct or to reward such teams using current academic management and promotion policies.
- There was (in 1992) no national policy to develop or to support education in PT.

All engineering fields feel they deserve more time in the curriculum, but there are limits on both faculty positions and money for new laboratories. Three- and four-year degree programs have very full curricula, so PT would have to displace something. This will probably not happen. Five-year diploma or MS programs probably have room for one course in PT fundamentals. While U.S. universities offer a few specialized MS and PhD degrees, graduates of such programs rarely have well-rounded backgrounds in PT because of the lack of PT courses.

Many disciplines are required to deal with PT problems:
- **Chemistry** - crystallization (morphology, defects), bulk and surface composition, surface reactivity and adsorption, surfactant synthesis, dispersion stabilization
- **Material Science** - hardness, modulus, crack propagation, strength, compressive behavior, ductility, plasticity
- **Chemical/Mining Engineering** - design and operation of economic processes to manufacture particles with the desired properties at high capacity, yield, and purity
- **Mechanical/Civil Engineering** - design, operation, and maintenance of hoppers, milling, conveying equipment
- **Physics** - design and use of measuring equipment, application of fields to modify solids behavior
- **Process Control Engineering** - design and implementation of process control from particle formation to packaging
- **Mathematics/Computer Science** - modeling of manufacturing processes and of particle interactions, simulation, visualization, and data handling
- **Information Science** - compilation of global literature into meaningful literature surveys, improved communications, and better transfer of information
- **Statistics** - development of efficient experimental programs, methods for data reduction and presentation

How Much has been Accomplished?

Much has happened since we posed the challenge to academia in 1992:

- 1992 The Particle Technology Forum (PTF) was approved by the AIChE. It provided a focal point for interdisciplinary and intersocietal exchange of information.
- 1993-94 The National Science Foundation funded four PT training courses for university faculty, with the expectation that they would introduce PT material into their courses.
- 1994, 96 The PTF held successful meetings; the next will be in 1998.
- 1994 Publication of “The Legacy of Neglect in the U.S.,”
- 1994 ERC-PT established at the University of Florida
- 1995 NSF funded the “Virtual Technology Market” concept. It is a Web site hosted by George Washington University (Washington, DC) at http://www.seas.gwu.edu/guest/vtm
- 1995 Publication of “Teach ‘Em Particle Technology”
- 1996, 97 Several new books, CD-ROMS, courses, modules, and Web sites (see below)

Who is Leading the Effort Now?

The PTF (http://www.eng.nsf.gov/ptf/) has formed a Task
Force on PT Education and has assigned working group leaders for:

- Particle Formation from Gases
- Crystallization and Precipitation
- Size Enlargement and Agglomeration
- Comminution and Attrition
- Tribology, Friction, and Interparticle Forces
- Particle Characterization
- Fluidization and Multiphase Flow
- Solids Flow, Handling, and Processing
- Particle Mixing, Segregation, and Classification
- Powder Mechanics
- Particle Reaction Engineering
- Simulation, Modeling, and Visualization
- Dispersion, Rheology, and Solid/Liquid Separation
- Deposition, Fouling, Erosion, and Wear

The ERC-PT (http://www.erc.ufl.edu/) has had a significant impact on education related to PT for many age groups during its three-year existence:

- **Precollege Awareness** - The University of Florida’s Center for Pre-collegiate Education brings in over 300 junior and senior high students annually. One activity is a presentation by the ERC-PT.
- **College Courses** - There are now three new engineering courses in PT.
- **Extension to Other Colleges** - Four course modules in PT are available.
- **Printed Resources** - One textbook has been completed and several are in preparation.
- **Undergraduate Research Projects** - About 60 are funded each year.
- **Graduate Research Assistantships** - Over 30 are funded each year.
- **Continuing Education** - Three courses in 1996-97 had 150 industrial participants.

New curricula are being developed in the schools listed below; the U.S. needs to launch many more like them in the next few years. New beginnings will provide new options.

- City College of New York: Undergraduate and graduate laboratory experiments
- American Filtration Society: Short courses coordinated between four universities
- New Jersey Institute of Technology: Undergraduate and graduate courses
- University of Pittsburgh: Coordinating virtual distance learning in PT for graduate programs at four universities
- Yale University: Courses in interfacial phenomena,

**What Remains to be Done?**

The PT community understands the stakes involved in having graduates trained in this field. We must generate a demand for such graduates in a way that can be understood by academia and government (and by industrial management).

- **Industry should specify in personnel ads that it wants engineers with awareness of PT basics.**
- **National technical societies should insist that education include PT examples.**
- **National technical societies must continue to provide specific sessions for the presentation of PT research papers.**
- **Authors should include PT topics in their chemical engineering texts.**
  - Faculty should provide PT examples in many courses and laboratories.
  - Universities (several) should offer coherent graduate training programs in PT. These programs should include a period of industrial internship.
  - Universities (several) should establish a multilevel structure for comprehensive continuing education in PT.
  - Federal agencies should recognize the need to fund equipment and building facilities to support PT research programs.

**How Can You Decide What to Change?**

University faculty should carefully consider the value of the elements in their courses according to where those elements fall on the S-curve of mastery as a function of time, $m = z^4/(1+z^4)$, where $z = (t-t_0)/(t_{CRIT}-t_0)$ (see Figure 1).

**The Emerging Stage** • In the early days (when $z < 5/8$), so little is known about the phenomenon that it can be mentioned in courses and textbooks only as an interesting and possibly useful phenomenon. We cannot teach what we do not understand. Industries may “bet” on success by investing research funds and personnel in the technology, but they recognize that their efforts may not result in commercialization. High temperature superconductors are an example of a technology in the emerging stage.

**The Vital Stage** • As the fundamental relationships become clearer ($5/8 < z < 8/5$), our understanding and ability to apply them to commercial activity is partial, but developing. Students trained in the area can make a significant impact on...
improving industrial operations. Industries may either keep secret or patent newly gained information. They can profit substantially from an advance that their competitors do not know or cannot practice due to patent constraints. Filtration is an example of a technology in the vital stage.

The Mature Stage • In the later years of mastery (8/5 < z), understanding is thorough, and excellent equipment and consultant assistance is widely available. It generally costs less to buy the technology than to practice it in-house, so college courses can simply summarize the material. People who want to specialize in the field will receive their advanced training from apprenticeship or courses taught in-house by the firms that specialize in that technology. Electric motors are an example of a technology in the mature stage.

We should admit that some technology elements currently occupying considerable space in the curriculum have moved from the vital to the mature stage and should be treated at less length, leaving room for the vital elements of PT. The goal of undergraduate engineering education should be to provide all students with an awareness of and a value for PT and with basic skills to build on. Graduate education should provide at least some experience with advanced PT concepts. At both levels, course and laboratory work should be supplemented with practical experience provided by summer work programs or internships.

Summary, a New Project, and a New Challenge

We have made good progress in the last five years. People at the highest levels of academia, government, and industry now recognize the value of PT. A number of programs in PT have been added to the few previously in existence, and the current programs have significant strength and momentum. The success of the current programs should attract others who wish to have similar success in helping graduates find employment.

It is now clear, however, that training faculty in PT and adding PT courses to the curriculum are not the answer for most universities. Instead, we shall have to rely on faculty who have a little background in PT to incorporate PT understanding and examples into their present courses. To facilitate this process, several participants at the Snowbird Conference agreed to develop a Web site through which multimedia educational modules contributed by experienced educators and reviewed by senior members of the PT community could be widely and inexpensively disseminated. A printed journal incorporating the modules will provide permanence, copyright protection, and concrete evidence of the significant professional contributions made by the authors. Since the meeting at Snowbird, the PTF has agreed to sponsor the project and to provide editors, and the ERC has agreed to host the Web site. There is now a demonstration site at http://erc.utl.edu/erpt/.

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National technical success will not come simply from funding national research programs and educational modules in PT. Research results are published quickly and benefit companies everywhere. Students who participate in nationally funded programs come to our universities from many nations and upon graduation are hired by companies from around the globe. Consequently, government funding will improve a nation’s competitive situation only if that nation’s industries make the earliest and best use of the research results and students. To do that they need savvy technology managers.

Here, then, is the challenge to educators for the next five years: You must produce graduates who are both knowledgeable in PT and interested in entering management. You must help convince present technology managers of the importance of PT in improving their operations. You might even consider making the transition from academia to industry yourself, where you can contribute directly to improving asset productivity for U.S. industry. In short, “Savvy technology managers: train ‘em, convert ‘em, or become one!”

REFERENCES

Particle technology is concerned with the characterization, production, modification, flow, handling, and utilization of granular solids or powders, both dry and in slurries. The technology spans a host of industries, including chemical, agricultural, food products, pharmaceuticals, ceramics, mineral processing, advanced materials, munitions, aerospace, energy, and pollution control. A need for incorporating the subject into the undergraduate and graduate engineering curriculum has been well recognized.\textsuperscript{1,2}

As a consequence of an NSF Combined Research and Curriculum Development (CRCD) grant, an interdisciplinary concentration of new courses in particle technology is now being developed at the New Jersey Institute of Technology (NJIT) by faculty members in several of its departments. The concentration consists of three principal courses: 1) “Introduction to Particle Technology,” designed for upper-level undergraduates and first-year graduate students; 2) “Current Research in Particle Technology,” intended for graduate students; and 3) “Experiments and Simulations in Particle Technology,” intended for upper-level undergraduates and first-year graduate students. It is believed that these new courses cover material that is substantially absent in established engineering curricula.

There are many challenges in developing this curriculum, many of them due to the fact that the scope of particle technology is so broad-based and interdisciplinary. The primary objective of an NSF-CRCD award is to bring the current research of the PIs and other researchers in the field into the curriculum. But since the subject of particle technology is so broad and diverse, it soon became apparent to the PIs that the students required a large amount of background material before the research material could be taught effectively. To meet this challenge, the introductory course was designed to contain such background material. It was also clear that one individual may not have the necessary expertise required to develop a comprehensive program of education or, in some cases, even a single course. Thus, a team of instructors was needed to develop the curriculum concentration, and the two advanced courses were staffed with more than a single instructor.

Another major challenge was to establish particle technology as an interdisciplinary academic concentration that was integrated into the engineering curriculum without adding extra credits or dropping existing requirements. This was met by introducing the three courses in such a way that a student could take one or more of them as an undergraduate elective. Moreover, while the first course provided the necessary background material, the other two courses were designed so that an undergraduate student with good academic standing or a graduate student could take them without having taken the first course. In addition, several key experimental modules from the laboratory course were incorporated into the core undergraduate laboratory courses so that every graduating engineer from either the chemical or the
mechanical engineering department was exposed to some aspects of particle technology.

Yet another challenge in this curriculum development was to present the basic concepts, industrial practice, and new research in particle technology without overwhelming the students, while at the same time exposing them to a new set of analytical and experimental tools required for problem solving. This challenge is being met, in part, by the development of an instructional laboratory and the development of user-friendly computer simulations so that the students (and the instructor) have access to these facilities that enhance the classroom instruction. Further difficulties arose due to the fact that it was necessary to employ equipment and software that are not routinely used in the current engineering curriculum, such as state-of-the-art instrumentation for characterization, mixing, and flow property measurement, as well as image analysis, computer simulations, and video animation systems. In addition, students must also be taught the use of associated software. Since the current curriculum does not have the infrastructure to accommodate this, our challenge was to develop an easy-to-use set of instructions and to train graduate students who would be available to help the students taking the courses. Thus, providing the proper background material for the wide variety of topics has been more demanding than delivering the material related to the PIs’ research.

COURSE DESCRIPTIONS

COURSE 1
Introduction to Particle Technology

As previously discussed, this course is intended to provide background material in particle technology. Since the material covered in this class is not available in a single book, several reference books were used.1–3 The course covers a variety of topics in particle technology, described below.

Particle Characterization • Determination of the shape and size of particles, sampling, shape factors, and fractal dimensions for irregular shapes, Stokes’ law/sedimentation, electrozone sensing techniques (Coulter Counter), radiation scattering methods (Malvern Mastersizer), optical size-measurement systems.

Coulomb Materials • Mechanics of Coulomb materials, yield criterion of granular materials, active and passive Rankine failure states, unconfined yield stress, angle of repose and internal friction angle, Coulomb’s method of wedges, Janssen’s equation for stresses on walls of bins and hoppers, Walter’s switch stress.

Hopper Design • Core flow versus mass flow, Jenike shear cell and yield locus, material flow function and flow factor to size hopper outlet and slope, consolidation and compaction effects during loading and unloading hoppers.

Conveyor Belts • Design based on handbook by manufacturer trade associations, conveyer characteristics, angle of repose, angle of surcharge, flowability, density, dustiness, wetness, abrasiveness, corrosiveness and temperature, power requirements, belt tension, and idler spacing.

Solid-Gas Separation • Aero-mechanical separators, wet scrubbers, electrostatic precipitators and filters, pressure drop, flow rate, grade efficiency and cut size to characterize devices, cyclone dry-separation.

Gas Fluidization • Purpose of fluidized bed, aeratable, sand-like, cohesive, and spoutable powders, bed pressure drop, minimum fluidization velocity, slugging, bed expansion, entrainment of solids in exhaust, and heat and mass transfer.

Suspensions and Sedimentation • Stokes’ flow, Faxen’s law, hydrodynamic interactions, corrections to Stokes’ law, “effective fluid” model of a suspension, effective velocity, Einstein viscosity, sedimentation speed in a dilute suspension.

Slurries and Suspensions • Forces on a particle in a fluid, terminal settling velocity, drag coefficient, Archimedes’ number, homogeneous suspensions rheological behavior, measurement devices, Newtonian, power-law, Bingham plastic and Casson constitutive equations, Arrhenius equation, temperature-reference method, laminar and turbulent flows of suspensions in pipes, mixing of powder in agitated tanks, saltation, Durrand’s correlation, vessel agitation, critical speed of an agitation impeller.

Particle Size Enlargement • Industrial applications, agglomeration methods, mechanics of agglomeration, inclined-disk agglomerators, fluidized bed, and drum granulators.

Particle Size Reduction • Crushing and grinding, forces in size reduction, Rittinger, Kick, Bond, and Holmes methods for energy requirements, mathematics of predicting product size distribution, description of crushing and grinding machines in industry, example of size distribution in hammer mill.

Collision Mechanics • Coefficient of restitution, planar impact of spheres, normal collision of elastic spheres, collision of frictional elastic spheres, collision of inelastic spheres.

COURSE 2
Current Research in Particle Technology

This course, intended for graduate students (but may also be taken by upper-level undergraduates with good academic standing), is theoretical in nature and emphasizes microlevel modeling for the understanding of macroscopic behavior. It includes mathematical modeling and computer simulations. Also incorporated into the course are recent research developments in the field that do not yet appear

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in standard textbooks.

The course requires team teaching and also uses guest lecturers. While the course content may change depending upon the instructor, the main topics include: contact/collision mechanics, including hard sphere and soft sphere contact modeling; computer simulations for dry granular flows, including stochastic, geometric, and dynamic simulations; computation of transport properties; modeling of granular flows; dynamics of small numbers of sedimenting particles; effective viscosity of a suspension; sedimentation speed in a suspension; modeling of granular and fibrous bed filtration and fluidized beds. Many of these topics involve examples taken from the research of the PIs. The course also requires development of computer simulation codes by the students.

Several guest lecturers from outside have already contributed to this course: Dr. P. Singh (Processing of Complex Fluids) from Los Alamos Laboratory; Dr. L.-S. Fan (Fluidization Engineering) from Ohio State University; Dr. O.R. Walton (Discrete Element Simulations of Granular Flows) from Lawrence Livermore Laboratory; Dr. C. Wassgren (Experiments and Simulations of Vibrated Beds) from Caltech; Dr. K. Leschonski (Particle Classification) from CUTECH, Germany; and Dr. A. Caprihan (Nuclear Magnetic Resonance Imaging of Highly Energetic Flows) from The Lovelace Institutes, New Mexico.

COURSE 3
Experiments and Simulations in Particle Technology

As part of the NSF-CRCD grant, a new combined research and instruction laboratory is being developed, containing a variety of experimental equipment that includes instructional as well as research equipment. The laboratory is still under development, and several new experimental modules are currently undergoing construction. The completed modules are:

Angle of Repose The students are asked to measure the angle of repose of a variety of granular materials using four different classical methods (fixed-height table, fixed-base cone, tilting table, and rotating cylinder). A digital camera and image analysis are used to measure the angle of repose from the four methods and results are compared.

Particle-Size Analysis Using Sieves Sieving, one of the simplest, oldest, and most inexpensive methods of determining particle size distribution, which is widely used in industry, is effective for sizes down to about 38 microns. The sieving apparatus used in our experiments is an Octagon 2000 Vibrated Siever with a set of sieves ranging from 25 microns (mesh #500) to 4.0 mm (mesh #5). The students analyze samples of coarse sand to obtain a size-distribution curve as well as the cumulative-distribution curve by weighing the residuals at each sieve. For the tested samples, the students also collect data to study the sieving rate.

Particle-Size Analysis Using Laser Diffraction Technique The students perform size analysis of samples obtained through a grinding experiment using a Malvern Mastersizer X Laser Diffraction particle-size analyzer. The samples analyzed had a size range from a few microns to about 100 microns. During the course of the experiment, the students learn about sample collection, preparation, and the use of the Mastersizer. The most basic task of sample collection is perhaps the most difficult, and we realized that a better sampling scheme would be required. The Mastersizer software allows for selecting different scattering theories and refractive index models. Students use both Fraunhofer and Mie scattering theories and also have the flexibility of changing the model used for the refractive index. For each case, the results such as the “mode” (of the size distribution) and the “residual” (of the fit of measured and computed scattering data for all the detectors) are recorded.

Size Reduction/Grinding with a Ball Mill For the basic ball-mill experiment, a ball mill (Paul Abbe) with a ceramic cylindrical jar and cylindrical Burundum Alumina as the grinding media is used. The students are asked to perform a simple grinding experiment to study the rate of change in the particle size distribution as a function of time. A challenge in this experiment is to find a suitable test material capable of demonstrating the main features of the grinding process within a 2- to 3-hour lab period. For the sake of demonstration, soft gravel-like material of size 250 microns to about 4 mm is utilized.

Students are asked to analyze the results for the time dependence of size distribution, power consumption, and specific surface area.

Material Testing by Jenike Shear Cell for Design of Mass Flow Hoppers The purpose of this experiment is to calculate parameters of a mass-flow hopper for a given test material. The main issue in hopper design is the material testing procedure that provides information about flowability and cohesiveness of the material needed to select the hopper slope and minimum outlet size. There are many different methods to test the flowability of the material, although the Jenike method (which gives the Jenike yield locus) is still considered the most reliable and is perhaps the most widely used technique in industry. There is a detailed standard procedure for using the Jenike apparatus (see Figure 1), as the variability and the scatter in the test data is found to be very wide if careful testing is not performed. Each yield locus is formed by plotting the normal stress (loading weight) versus the prorated shear stress for at least three operating points. For each operating point on the curve, the material must be pre-consolidated by the consolidating weight (see Figure 2), and then the shear test must be performed for a
chosen loading weight (Figure 1), so that the loading weight is less than or equal to the consolidating weight. Students test materials such as flour, powdered sugar, and cornstarch. Highly cohesive materials (e.g., cornstarch) pose difficulties in obtaining reliable results. We found that the test apparatus was not very user friendly, and the task of complete testing is tedious, generally requiring 5 to 6 hours.

**Study of Rise of a Single Large Sphere in a Vibrated Granular Bed** Size segregation is often an undesirable outcome of handling and/or processing operations of bulk solids. In general, a large ball placed at the bottom of a vibrated bed will rise to the surface. In the laboratory sessions, the students examine various behavioral regimes of the vibrated bed and make observations of the rise time of the large particle at different operating conditions.

**Dilatometer Measurement of the Minimum Sintering Temperature of Fluidized Solids** Many of the processes using fluidized beds operate at high temperatures, which cause softening and/or partial melting (sintering) of the solids' surfaces, thereby requiring higher gas velocities to keep the bed in the fluidized state. The purpose of this experiment is to measure the minimum sintering temperature $T_s$ (the temperature at which thermally induced surface softening and sintering begins), an intrinsic property of the solid-particle surface. A relatively simple procedure to estimate $T_s$ makes use of constant-rate dilatometry to obtain the elongation-contraction versus temperature curve for a porous rod composed of the granular material in question (see Figure 3). In the experiment, a Theta Industries-Econo 1 dilatometer is used to heat a small sample of powder (about 1.2 grams) at a constant rate (maximum is $15^\circ$C/minute) to temperatures as high as $1600^\circ$C. Students set up and program the dilatometer to operate overnight at a constant heat-

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**Figure 1.** Jenike shear tester: Schematic above and photograph at left.

**Figure 2.** Material being pre-consolidated for Jenike shear test.

**Figure 3.** Schematic diagram of a dilatometer used for measuring minimum sintering temperature of powders.
ing rate using alumina powder in a Nitrogen atmosphere. Results are analyzed the next day to determine $T$.

\section*{Particle Sedimentation}

The falling-ball viscometer is the first in a sequence of experiments concerning suspensions and sedimentation. The apparatus consists of a glass cylinder (100 cm long by 10 cm diameter) containing a viscous fluid (UCON fluid 50-HB-3520, manufactured by Union Carbide), as shown in Figure 4. Small numbers of particles placed in the fluid at the top of the cylinder may be observed as they sediment along the axis of the cylinder. Students receive instruction on the basic theory of sedimentation at low Reynolds number and its application to size segregation and characterization. Using the manufacturer’s specifications of the physical properties of the fluid, a collection of particles, a balance, a thermometer, a meter stick, and a stop watch, students are asked to investigate some of the physical characteristics of the system. Hydrodynamic properties investigated include particle-wall and particle-particle interactions, inertial effects, and thermal effects. Particular emphasis is placed on having students explain variability in observations. Reports are kept on file and future students will be asked to analyze their data and to reconcile their results with those of groups from previous years.

\section*{Other Planned Experiments}

Other experiments will be selected from: blending and mixing; segregation in poly-disperse vibrated beds; conventional fluidized bed; rotating fluidized bed; core-flow/mass-flow hoppers; particle-collision properties; non-intrusive tracking in granular flows; dry particle coating; simulation and visualization of granular flows.

\section*{SPECIAL COURSES}

As a part of curriculum development, two special courses were also given: “Fluid-Particle Flows at Low Reynolds Number” (offered as Special Topics in Applied Mathematics by Prof. J. Luke) and “Image Analysis for Applications in Particle Technology” (by Prof. R. Dave). These courses had the objective of “trying out” part of the material that would eventually be included in the new three-course particle technology concentration.

\section*{ACCOMPLISHMENTS}

Some of our major accomplishments are:

- Formation of an Advisory Board with particle technology experts from industry and academia. The board comprises representatives from 12 industrial companies and 6 universities. Board meetings have been held every March, beginning in 1995.

- Development of and offering the introductory course, “Introduction to Particle Technology,” in the fall of 1995 and the fall of 1997 by Dr. I. Fischer. Approximately 20 students, both undergraduates and graduates, were enrolled each semester.

- Offering of the graduate course “Current Research in Particle Technology” by Dr. R. Dave during the spring of 1996 and by Dr. A. Rosato during the spring of 1997. Approximately ten students were enrolled each time.

- Offering of two special courses

- Designing and building the new combined research and instruction laboratory.

- Offering of the laboratory course “Experiments and Simulations in Particle Technology” in the fall of 1996 and again in the spring of 1998 by Dr. R. Dave.

\section*{SYNERGY OF EDUCATION AND RESEARCH PARTNERSHIPS}

During the course of this project, we recognized that a number of partnerships were required for a successful completion. The first step toward developing these partnerships was through the Advisory Board (AB), which has been of significant help in providing guidance and advice as well as technical and financial support. As an example, four guest speakers, two of whom are members of our AB, delivered three-hour lectures to the students in the graduate course. Also, one industrial member of the AB presented a lecture on particle-size-analysis techniques in the laboratory course, and another representative from a member com-
pany spent a full day with our students on the Jenike shear testing experiment. Our partnerships also include collaborations with a number of universities, including the NSF-ERC in Particle Science and Technology at the University of Florida.

While research activities in the area of particle technology have been ongoing for several years at NJIT, the CRCD award has served as the impetus for developing a number of new research collaborations as well as the formation of the Particle Technology Center at NJIT. Readers can access its web site at

http://www-ec.njit.edu/ec_info/image2/ptc

Moreover, our efforts have been recognized at NSF (we were asked to showcase our CRCD program as part of the exhibition held at the 1996 annual ASEE meeting at Washington, DC), by other academics, by recognized experts from industry, and most recently by the State of New Jersey. The first and fourth authors received one of the new R&D Excellence Awards from the state of New Jersey to establish a Particle Processing Research Center in collaboration with Rutgers University. Readers can access its web site at

http://www-ec.njit.edu/ec_info/image2/PPRC/

This program provides seed money ($300,000/year) for five years to establish a long-term, self-supporting program with a focus on basic science with industrial relevance, having intermediate and long-term commercialization potential. In summary, our experience in forging partnerships has proven very beneficial and we believe that even more can be gained from these partnerships in the future. The synergism between research and education is obvious, and the success of both depends heavily on partnerships.

CONCLUSIONS

The development of a curriculum concentration in particle technology is ongoing and our experience has been quite positive so far. Despite challenges due to the broad and interdisciplinary nature of the subject material, we have made substantial progress. All three of the new courses have already been offered twice. In the near future, we will focus on dissemination of the materials that we have developed. Currently, our goal is to put sample notes and examples on our web sites and to provide several modules from each course to colleagues for use at other universities. We will also share information on our laboratory development, simulation codes, and video animations.

The course material presently focuses more on the “mechanical” aspects of particle technology as compared to the “chemical” aspects. This is in part due to the fact that three of the five team members are from the Mechanical Engineering Department and have served as principal instructors of the courses offered so far. Current efforts are to make the material more balanced and include chemical reactors involving particles, mechano-chemistry, and suspension rheology so as to attract more students from chemical engineering and other engineering disciplines. In the next few months, several experimental modules will be incorporated into the core undergraduate laboratory courses, and the results of that experience will be reported in the future.

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REFERENCES

G
iven the time constraints in most undergraduate fluid-
mechanics courses, any instruction in fluid flow
involving particles is typically limited to the most
basic concepts, such as determining the pressure drop in a
packed bed or calculating the minimum fluidization veloc-
ity. A similar situation exists with instruction in single-phase
turbulent flows when students are introduced to the mixing-
length concept applied to pipe flow. But when these same
students graduate and enter industry, they are confronted
with a host of complex flow processes, both single phase and
multiphase, for which modeling could aid in scale-up, de-
sign, and optimization. Hence, students should be made
aware of the computational fluid-dynamics tools available to
approach these processes. [11]

This paper discusses a way in which computational fluid
dynamics software can be easily incorporated into an under-
grade transport course and how, through the use of soft-
ware via case studies, students can be exposed to more
concepts and practical examples of fluid-particle flow.

WHAT IS CFD?
The acronym CFD stands for computational fluid dynam-
ics. CFD codes numerically solve the mass-continuity equa-
tion and the differential momentum balance for fluid-flow
situations over a specific domain set by the user. The do-
main can range from a simple mixing tank to an intricate
mold or a complex pipeline network. The flow can be
laminar or turbulent.

In the case of turbulent flow, several turbulence closure
models are typically available from which the user can choose.
Numerical solution of the energy balance and species contin-
uity equation(s) can be coupled to the flow equations to
describe heat transfer and chemical reactions in flow situa-
tions. In addition, several CFD codes have multiphase capa-
bilities and can be used to simulate a dispersed phase (par-
ticles or droplets) in a continuous phase, again with the
possibility of coupling with heat transfer and chemical
reaction. The simulation results can be given in numeri-
cal output or displayed graphically or pictorially in sev-
eral different formats.

WHY USE CFD SOFTWARE
IN UNDERGRADUATE TRANSPORT COURSES?
There are several excellent reasons to incorporate CFD
into transport courses.

- Students aren’t left with the notion that the em-
pirical approach is the only method to tackle most
real-life processes involving fluid flow.

If students are exposed only to “idealized” fluid-flow cases
in the curriculum, for which application of theoretical con-
cepts results in the solution of a one-dimensional ordinary
differential equation or an algebraic equation, it is very
easy for them to come away with the notion that theory is useless
for most real-life flow situations. Empiricism seems the only
way to approach flow processes that don’t fit directly into
the molds that they have studied. Through exposure to CFD,
students can gain an appreciation for the fluid-flow tools
available (still based on the theories they have learned) that
can be applied to real-life processes.

- Students can visualize the flow behavior.

Once a fluid-flow situation is analyzed theoretically or the
governing principles are discussed, that same situation can be visualized using the computer. This visualization of the flow phenomena can significantly facilitate and enhance the learning process, especially for the visual learner. CFD software makes flow visualization easy. Students can simulate flow processes in a transient or steady-state mode. Flow patterns can be displayed via velocity contours, velocity vector plots, or graphs of velocity profiles. A color scale indicates the magnitude of the velocity for each phase or the solids volume fraction.

The graphics are very flexible and user-friendly and are much better than any professor could draw on the chalkboard or overhead projector using different colored pens! Once a fluid-flow situation is analyzed theoretically or the governing principles are discussed, that same situation can be visualized on the computer.

- Students can explore the effect of changes in system geometry, system properties, or operating conditions.

A key element in flow visualization exercises is exploring the effect of different parameters. Using CFD, students can quickly change the size of the pipe, viscosity of the fluid, size of the particles, velocity of the feed, etc., and see the resulting changes in the flow behavior. This type of parametric analysis also ties in nicely with a discussion of dimensionless groups and geometric and dynamic similarity.

- Students can compare the simulation results using CFD with the analytical results obtained in the classroom or in their homework.

A comparison between simulation results and analytical results gives students confidence in both their hand calculations and the CFD code. These comparisons can be a basis for the treatment of numerical methods applied to fluid-flow problems. They can also be a starting point for increasing the complexity of the problem for which only a numerical solution is possible.

- CFD is used in many companies, such as Dow, DuPont, Alcoa, P&G, Shell, Exxon, Chevron, etc., and in many different industries such as chemical, oil, automotive, pharmaceutical, etc.

If our students have experience with tools that they will use in industry, they will be productive more quickly.

- Students like it!

Students like the user-friendliness of the CFD codes, the colorful graphics, and most of all, they like envisioning new designs for flow processes and trying them out.

CHOOSING A CFD CODE

A number of CFD codes are commercially available, but the choice can be narrowed somewhat as certain codes are written to target specific applications, such as non-Newtonian flows.

For fluid-particle flow, CFX* and Fluent** currently have the majority of the industrial multiphase market. CF DLLIB is another multiphase flow research code available, developed by Los Alamos National Laboratories.*** For the academic user, the licensing fee for the object code of Fluent and CFX is cut substantially from the industrial rate and is typically around $2000-$3000 per year. In developing the case studies shown in this paper, we have used the Fluent code. It has the benefit of a built-in generation package for quick and easy setup of simpler flow geometries by the students, it has extremely user-friendly input and output formats, and it can be used successfully by undergraduate students with little training. Tutorials that go step-by-step through the simulation of various single phase and multiphase flow examples are available with the user guides.

Ms. Ann Pertuit, who prepared the Fluent graphs shown in this paper, taught herself the Fluent code when she was a sophomore chemical engineering student by going through these helpful tutorials. I know of several schools, including Carnegie-Mellon University, that have successfully integrated the Fluent code into their transport courses with very positive response from the students.

CFD MODELS FOR FLUID-PARTICLE FLOW

Multiphase flow involving particles can be modeled using the Lagrangian approach or the Eulerian approach. In the Lagrangian approach, a separate equation of motion is integrated for each particle.

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and the motion of individual particles is traced subject to forces on the particles as specified by the user. This approach is typically used for very dilute phase flows (solid volume fractions less than $10^{-3}$) due to computer-storage limitations and the assumptions made in developing the modeling equations. It is a convenient approach when different properties/conditions need to be specified for individual particles. Coupling between the continuous phase and the dispersed phase occurs through the drag force.

In the Fluent code, a description for modulation of fluid-phase turbulence by the presence of particles can be specified by the user. For example, if the $k-\varepsilon$ turbulence-closure model is used to describe the turbulent stresses in the continuous phase, the source term in the transport equation for the turbulent kinetic energy can be specified by the user. In the current version of Fluent (version 4.4), particle-wall collisions (but not particle-particle collisions) are included in the Lagrangian formulation.

In the Eulerian approach (or “two-fluid” approach), the dispersed phase is described as a continuum, so it is well suited for dense-phase flows. In this approach, however, stresses must be specified for various terms generated from averaging procedure used to formulate the two-fluid governing equations. For example, the particle-phase stresses must be specified. The user can set a constant solids viscosity, describe these stresses with a user-defined algebraic closure that can depend on any of the flow variables, or, for larger particles in which hydrodynamic interactions are negligible, employ a kinetic-theory model that is available in the Fluent code.

In the kinetic theory model, particle-phase stresses are generated from particle-particle collisions and are described in an analogous fashion to molecular collisions in a gas accounting for the fact that particle-particle collisions are inelastic. Since the solids viscosity is dependent on the magnitude of the particle velocity fluctuations associated with the particle collisions, the continuity and momentum balances are supplemented with a balance of kinetic energy for these particle-velocity fluctuations. In the kinetic-theory model, the user specifies the collisional behavior of the particles in terms of a coefficient of restitution (equal to one for a perfectly elastic particle-particle collision).

In the current (4.4) version of Fluent, a boundary condition of zero flux of particle fluctuation energy is given for the particles. In the next release of Fluent (scheduled for spring 1998), kinetic energy transfer with the wall during particle-wall impacts is accounted for. Version 4.4 includes particle-phase stresses that are due to fluctuations associated with individual particles; Version 4.5 will include particle fluctuations associated with clusters of particles, or particle-phase turbulence, as well as friction between particles.

INTEGRATION OF CFD

The CFD code can be introduced in one lecture. Typically, a graduate student who has most recently taken the full training course for the CFD code at the company site introduces the students to the code. The key steps that must be followed for any simulation should be outlined. They include allocating memory, defining the domain, setting the cells, choosing the physical model and boundary conditions, defining the physical constants, saving the case file, running the program, and saving the data. Detailing these steps in a supplementary handout is helpful (a sample of such a handout will be sent on request by contacting me at jlds@ecn.purdue.edu). For homework, students should work through the tutorial on laminar flow in a pipe. They should practice generating and modifying the grid and viewing the results in the different formats.

Figure 1 shows the developing velocity profiles for laminar flow in a pipe. The results can also be displayed using velocity vectors or velocity contours. This figure was generated with a 250x10 grid. Students can compare their results for fully developed flow to the analytical solutions they have obtained in class. After they are comfortable with the pipe-flow example, other geometries can be explored. Good homework problems include analyzing the two-dimensional laminar flow pattern in a given geometry, expanding on the analogous one-dimensional, fully developed flow solution that was derived in class. In a heat transfer course, students can couple the flow equations with the energy balances to determine wall heat flux in a convection situation.

Treatment of turbulent flows at the undergraduate level can be enhanced through the use of CFD. I spend one lecture introducing the students to the various types of closure models commonly available in CFD software packages, focusing on the $k-\varepsilon$ model, which is the most widely used. I discuss both the high Reynolds number $k-\varepsilon$ model and the use of wall functions, as well as the low Reynolds number $k-\varepsilon$ models. For homework, students should go through the tutorial on turbulent pipe flow. This tutorial is basically the same as the laminar pipe-flow tutorial, with changes in the physical model and one parameter (pipe diameter or fluid velocity) to increase the Reynolds number. Figure 2 shows the turbulent kinetic energy contours with Re=32,000. Other flow geometries can be explored for homework problems. Students should be cautioned in the lecture, however, about the shortcomings of the $k-\varepsilon$ model and inappropriate application of this model for certain types of flows.

FLUID-PARTICLE CASE STUDIES

Once the concept of drag is introduced to the students, it is a simple extension to discuss the dynamic equations for a particle in dilute phase transport. Figure 3 presents a
Figure 1. Laminar flow.

Figure 2. Turbulent flow.

Figure 3. Sand particles injected into a 2-in. ID pipe—Lagrangian Method

Figure 4. Turbulent flow of sand in a vertical pipe—Eulerian Method

Figure 5. Fluidized bed.

Figure 6. Coal combustion
Lagrangian simulation of 110 \( \mu \text{m} \) sand particles fed into side inlets along a pipe length and shows the velocities and trajectories of the particles as they move down the pipe and impact the pipe wall.

Another excellent case study (not shown here) is one in which a comparison is made between the velocity magnitudes and trajectories of particles with different physical properties. Students also enjoy trying different geometries and performing parametric studies.

For dense-phase flow, students must be introduced to the two-fluid concept. At the undergraduate level, this need not be done in a rigorous fashion with a lengthy discussion of local averaging the point equation of motion of a single particle. Rather, the governing equations and the continuum concept applied to the particle phase can be discussed in a more general way by analogy to a single-phase fluid. For larger particles that engage in particle-particle collisions, the kinetic theory concepts for describing particle-phase stress can be introduced in the same manner. Figure 4 shows solid-volume fraction contours in a case study involving gas-solid flow in a vertical pipe with a uniform inlet solid-volume fraction of 10%. In this figure, the kinetic theory model was used to describe the solid-phase stresses, and the coefficient of restitution for the particles was 0.9.

Another example involves simulating a fluidized bed when the topic of fluidized beds is discussed in the traditional lecture. Figure 5 presents a plot of the sand-volume fraction contours in a fluidized bed with a center gas jet at 0.117s of real time. As time progresses, students can watch the evolution of the gas bubble in the bed. In this simulation, the kinetic theory was again used to describe the particle-phase stress.

Once students gain confidence in using CFD software, the range of viable case studies is endless. Multiphase flow with chemical reactions is possible. Figure 6, which was generated by following one of Fluent's tutorials, shows the concentration of CO\(_2\) in a coal burner. Students can specify the type of chemical reaction, the chemical species involved, and the kinetic rate constants, in addition to all of the flow parameters, in order to observe the evolution of reactant and product concentrations in the flow field.

**COMPUTER REQUIREMENTS**

The CFD codes can typically operate on any platform (high-end PC, workstations, supercomputers). For the Fluent code, the following system requirements must be available:

**Hardware**
- CPU: Pentium family of processors, DEC, Sun, SGI, IBM, HP, Cray
- Video graphics device with minimum 1024x768 resolution and 256 colors
- CD-ROM
- 3-button mouse is recommended
- X-windows systems for UNIX operating systems

**Operating System**
- Microsoft Windows NT 3.51 or higher
- UNIX-platform and operating system version specific
- Microsoft Windows 95
- Alpha Windows NT

**Memory Requirements**
The memory requirements vary with the problem size/grid size. Fluent requires a minimum of 64 MB RAM. Three-dimensional simulations require at least 128 MB RAM.

**Disk-Space Requirements**
- 20 MB - Intel Windows
- 100 MB - UNIX systems

When the CFD code is being used by an entire class, it is best to have it installed on one or two workstations that can be accessed within the network by other machines so all the students do not have to be physically sitting at those one or two workstations. Students can then use the keyboard and display of another machine to input their data and see the results. A handout detailing how to access the CFD code remotely in your local university computing network is helpful.

**A FINAL NOTE**

This paper has pointed out the benefits associated with integration of CFD into undergraduate transport courses and how CFD software is a convenient vehicle for opening the door to the treatment of complex flows, such as fluid-particle flows, at the undergraduate level. Hopefully, the reader has been persuaded to give it a try.

**ACKNOWLEDGMENT**

The author is grateful to Ms. Ann Pertuit, a junior student in chemical engineering at the University of Arizona, for preparing the Fluent graphs.

**REFERENCES**


Chemical Engineering Education
Dear Editor:

Bravo to Prausnitz (in the spirit of Aris) for casting our gaze in the direction of the humanities. Will chemical engineering produce its Charles Percy Snow, who caused a stir about three decades ago urging a “humanities...literature” culture bridge swing to a “science...technology” culture in his The Two Cultures: A Second Look through courses such as molecular biology. Prausnitz has delightful references to Bohr, Chagall, Haber, Silone, and others, but only a limited number of them. Can someone point out a textbook with others?

Sincerely,
Dale L. Schruben
Chemical Engineering Department
Texas A&M University, Kingsville

To the Editor:

We have produced a thermodynamics “slide show” at Iowa State University consisting of computer-generated images of fluid-phase equilibria with supporting text. The drawings show VLE situations for binary, ternary, and quaternary systems and combined VLE-LLE in a ternary. Pressure, temperature, and composition data in the sub-critical ranges are based on the Peng-Robinson equation using conventional mixing rules. Calculations were performed by the various flash routines within ASPEN PLUS. Critical points and curves were determined by the method of Heidemann and Khalil.

Open Inventor graphics software running on a Silicon Graphics workstation was used to generate the three-dimensional visualizations (binary PT-x-y, ternary composition prisms, quaternary tetrahedrons). Bubble-point and dew-point curves and surfaces are distinguished using color and transparency, and static images are clearly labeled. Some of the drawings can also be zoomed, rotated, and sectioned to demonstrate phase-diagram geometries and show the importance of viewer orientation.

The Silicon Graphics “Showcase” utility was used to make the supporting text slides (approximately 45). The slide show was first given in November 1997 at the final examination of Kong Tian for the M.S. degree in chemical engineering. A Silicon Graphics “Presenter” was used for projecting the images onto a large screen.

We would like to offer the complete show at no cost to anyone having the Silicon Graphics equipment (and standard Showcase utility) needed to run it. The show provides an interesting and effective way to alert students to the visualizability of thermodynamic information and to the fundamental hyperdimensionality of the data.

Those interested should contact Professor Jolls. Computer files can be retrieved via ftp and will include sufficient information to enable users to run them in the proper sequence. A videotaped version of the slide show will be available later this spring.

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To The Editor:

I was interested, and indeed proud, to note that three of the articles in the winter ’98 issue of CEE had a direct relationship to the Department of Chemical Engineering at the University of New Brunswick (UNB).

• Professor Arvind Varma (profiled as the ChE educator) graduated with a masters degree from the fledgling department in 1968.

• Dr. S. Farooq, my own former student at UNB (PhD, 1990), now a faculty member at the National University of Singapore, was author of an interesting article describing the development of an adsorption experiment for the undergraduate laboratory.

• Finally, Dr. Guido Bendrich, a UNB professor who obtained his PhD from McMaster University under Prof. Les Shemilt, the founding Head of the UNB department, presented an article describing a new communications course.

Not a bad record for a small department!

Sincerley,

Douglas M. Ruthven, Chair
Chemical Engineering Department
University of Maine
Experiments, Demonstrations, Software Packages, and Videos for PNEUMATIC TRANSPORT AND SOLID PROCESSING STUDIES

GEORGE KLINZING
University of Pittsburgh • Pittsburgh, PA 15261

Pickup and Saltation Velocities • In order to design a pneumatic conveying system, a knowledge of the proper conveying velocity is essential to transport the material efficiently. The pickup velocity from the bottom of a transfer line and the saltation velocity at which the particles salt out of the flow are essential. These velocities can be determined experimentally with the basic flow system shown in Figure 1. Several of different parameters influence these velocities: particle size, particle density, particle shape, cohesiveness, pipe diameter, and gas density. Work in our laboratory has developed a correlation for the particle pickup velocity.\(^1\) Videos can be easily prepared of the pickup and saltation phenomena and can be shown in the classroom. Further details are given at the end of this article.

Avalanching • The release of particles onto a self-forming pile of particles (avalanching) presents some interesting observations that possibly can be used to characterize the particles themselves. This characterization can have a bearing on the way the particles behave in pneumatic conveying and other solids processing operations. A simple device to deliver particles to a pile and for observing the behavior of particle avalanching can provide students with a unique experiment to further their knowledge of particles. Figure 2 shows this experiment, and Figure 3 shows a method of classifying the avalanching with particle size.\(^2\) Here, the weight of each avalanche that occurs is plotted against the percentage of avalanches having a weight greater than this value. Each material shown has a particular characteristic curve. Again, video taping can be carried out to provide an additional classroom resource.

Pneumatic Conveying Flow Loop • A simple flow loop is shown in Figure 4. Every loop must have an air supply, a feeder from a bin or a hopper, a transport line, and a collector. House air can supply the transport gas for a 1- or 2-inch...
Highly polished surface inside collection hopper

Figure 2. Avalanching experimental setup.

The most common type of feeder is a rotary valve, which can be the most expensive component of the system. The collector can be a cyclone, especially when collecting millimeter-or-larger-size particles. These units can be easily constructed using the standard design equations for cyclones. The loop can be instrumented with relatively inexpensive pressure transducers coupled with a computer measuring scheme, which can provide a wealth of information about entrance effect, horizontal and vertical conveying differences, and bend pressure losses. Further details can be found in the Appendix to this article.

Bins and Hopper Flows • Delivery of the solids from a bin or hopper through a feeder to a conveying line is essential to all solids transport operations. If the material will not leave the bin or hopper, nothing will be conveyed. A simple two-dimensional experiment to measure the effect of the wall angle of the bin or hopper on the type of flow can be easily constructed. By using different colored particles, one can follow the flow patterns and velocities. Using a video or Polaroid cam-

Figure 3. Avalanching graphical analysis.

era can provide a good record of the experiment. The detailed dimensions of this wedge unit are given in the Appendix to this article.

Bend Erosion • Demonstration of the process of erosion in conveying can be carried out by using a marking pen and a glass bend. A grid can be drawn on the inside of the bend, be it a short radius or a tee. This marked bend can then be subjected to the flow conditions with particle flow. As time goes on, it can be seen that the marking will erode in certain regions of the bend. The time of operation is short, and video taping of the process can provide a clearer understanding of the flow patterns in such operations.

Figure 4. Pneumatic conveying flow loop.
In order to impress on the students the basic principles described by mathematical analysis, one should search for appropriate demonstrations for classroom use. We have developed a few of these demonstrations that can give the instructor a small tool box to help in teaching solids-handling principles.

**Plug Flow** • Following a demonstration first employed by Peter Arnold (Wollongong University), we constructed a Plexiglas column with an aluminum disk connection to a cable that threaded through the column over a pulley and attached to a pull-spring scale. A plug of bird seed approximately 6 inches long provided the plug for study. Measuring the force needed to move the plug can be recorded at different plug lengths, indicating the nonlinear force relationship with the plug length. Adding a small amount of air at the bottom of the column will slightly fluidize the plug and permit significant reduction of the force required to move the plug. The details of this device are seen in Figure 5.

**Wall Pressure** • Likewise, Peter Arnold has shown that a paper tissue placed at the end of a tube and tied with a rubber band can support a column of solids because the walls support a significant portion of the weight of the particles. This unit is also shown in Figure 5.

**Fluidization** • A simple fluidization pipe can show gas fluidization by simply blowing through a tube connected to an air distributor leading to a fluidizing chamber containing particles. Figure 6 shows this device.

**Bin and Hopper** • John Carson (Jenike and Johanson, 1 Technology Park Drive, Westford, MA 01886) has provided small-bin demonstration devices in an hourglass-type unit made of Plexiglas that show mass flow with a steep bin angle and funnel flow with a shallow bin angle. He has educated a large number of students with this excellent demonstration (see Figure 7).

**Segregation** • This process can be shown easily through the movement of a mixture of large and small particles in a Plexiglas chamber having internals similar to a bin or hopper. The larger particles are seen to migrate to the outside of the forming pile, while the small particles stay in the center. G. Enstad (Telemark Institute, Norway) first constructed this device to observe the segregation phenomenon. Figure 8 shows the details of this device, which has four chambers arranged in an internal X-geometry.
Troubleshooting Pneumatic Conveying System

Troubles in your system may be due to any of the following possible reasons:

- Loss of conveying air was found to be a possible cause.
- Filled receiver vessel is a possible cause.
- Explore further whether material coating inside the pipe may be a possible cause.
- Change in solids throughput demands more careful analysis.
- It appears that there is a physical obstruction in the conveying line.

** End - press ENTER to continue.

Troubleshooting Pneumatic Conveying System

Choose one or more of the following listed causes:

- Yes
- Loss of conveying air
- Filled receiver vessel
- Material coating inside conveying line
- Change in material being conveyed
- Increased feed rate
- Physical obstruction in conveying line

1. Use arrow key or first letter of item to position the cursor.
2. Select all applicable responses

Figure 8. Segregation flow demonstration.

Figure 9. Artificial intelligence troubleshooting example.

A number of computer packages have been developed in our laboratory that provide the student with a wide cadre of tools to help design a pneumatic conveying system. A number of computer packages have been developed in our laboratory that provide the student with a wide cadre of tools to help design a pneumatic conveying system.

OPSD • This program is designed to predict the energy losses in a dilute phase-conveying system using the basic energy equations for two-phase flow. The calculations account for a wide range of geometries, including long-distance pipe stepping calculations.

Nuselect • This is an artificial intelligence package to help the design choose the best conveying system offering both dilute and dense phase systems with different types of air movers.

Feeder • Another artificial intelligence package, crafted with the help of experts, to choose the most appropriate feeder for an application.

Panacea • Once a system is in operation, it will invariably develop operational difficulties. This artificial intelligence package provides a first-aid approach to remedying a system, providing recuperation of the operation or moving the system to a more optimum point (see Figure 9).

Cyclone • Using a series of common design strategies for cyclones, this program helps the designer select the approach cyclone by estimating the operating characteristics and dimensions.

Computer Packages

A convenient way to record an experiment is to video tape the phenomenon. In our laboratory we have video taped a wide variety of our experimental endeavors. In some cases, this record could be analyzed quantitatively to develop predictive models. In other cases, further understanding of the process was gained by viewing the video record.

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4. Pelczarski, E., PhD dissertation, University of Pittsburgh (1964)

APPENDIX

Pickup and Saltation Velocities

The pickup-velocity experimental rig consists of a trans-
Imagine for a moment that you are a newly graduated chemical engineer, eager to start your first assignment with a major chemical company. Your new boss teams you up with a group of other engineers to work on the design of a new production facility. Over the next few weeks you pore over the plans to become familiar with the overall operation.

You notice right away that the process has some reactors, very few gas or liquid phase operations, and no distillation columns. What it does have are a lot of hoppers, bins, mixers, conveyors, extruders, filters, and dryers. Much to your dismay, your personal reference library of chemical engineering textbooks seems to be woefully inadequate for designing these solids processing operations.

How often does it happen that a new chemical engineer’s first assignment involves operations with solid particles? Perhaps more frequently than you might expect.

Ennis, et al.,[1] report that in 1985 and again in 1992, DuPont found that about 60% (by value or volume) of its products are sold in particulate form, while another 18% have particulate additives. Similarly, 50% (by volume) of the Dow Chemical Company’s products are solids. The total amount of solids handled in the plants may be three to four times that of the product volume.

Companies such as DuPont and Dow Chemical Company have thousands of major unit operations involving solid particles. Each operation requires engineers and technicians who understand the relevant areas of particle technology. The probability is high that newly hired chemical engineers will be assigned to operations involving particulate solids.

One author (KJ) has had experience in teaching solids processing to over 300 practicing engineers in the last five years. A remark he has heard frequently is “I wish I had been taught this in college.”

The new engineer in our introduction lacks training in the design of fluid-solid processing. This is not unusual. Others have noted a similar deficiency in engineering education.[2,3] A recent survey shows that there are a few courses being taught at U.S. universities,[4] but there are no undergraduate programs devoted to solids processing as there are overseas.[5] Most engineering curricula are full, with little room for additional courses. Nevertheless, some schools are making room in their curriculum[6] or are providing elective specializations in solids processing.

The purpose of this paper is to describe a senior undergraduate course on solids processing that is team-taught at
The course... is team-taught by academia and industry and has a mix of theory and practical design in addition to lectures and hands-on experience for the students. . . . we feel it covers many of the important topics in solids processing that engineers need to know before going to work in today's chemical process industries.

The University of Akron.

SOLIDS PROCESSING COURSE

The solids processing course at The University of Akron is unique in that it is team-taught by the two authors, one from academia and one from industry. The course is sponsored by the National Science Foundation by a one-year grant under the GOALI program. It is design-oriented by intent to satisfy ABET requirements. The mechanics of the course include two lecture periods per week (75 minutes each), an in-class plant-design project, group projects that the students work on outside of class, and a plant tour. In the future we plan to add a laboratory component to the course.

The course topics are listed in Table 1 and references used in the course are given in Table 2. The course started out with a discussion of the design of chemical plants and the types of solids processing and handling equipment found in many of the plants. Several class periods covered properties of individual particles and the various methods of particle measurements of sizes and size distributions. Particle-fluid mechanics were also discussed for individual particles.

### Table 1
#### Topics Covered in the Course

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>SUB-TOPICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>Course organization; projects; grading</td>
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<tr>
<td>CPI Perspective</td>
<td>Examples of processes that handle and separate solids; discussion of typical operations (storage hoppers, conveying, filters, drying, reactors, etc.) in a broad perspective.</td>
</tr>
<tr>
<td>Particle Size and Shape</td>
<td>Methods of measuring particle size; definitions of particle size, mesh size; typical sizes of common materials</td>
</tr>
<tr>
<td>Size Distributions</td>
<td>Definitions of averages, frequency, cumulative distributions (number, area, mass); choice of mean particle size</td>
</tr>
<tr>
<td>Drag Force on a Spherical and a Non-Spherical Particle</td>
<td>Drag coefficient; terminal velocity; sphericity; correlations</td>
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<tr>
<td>Bulk Properties of Solids</td>
<td>Angle of repose; porosity; loose, normal, and dense packing; bulk density; slurry viscosity; coefficient of friction; axial-to-lateral stress ratio</td>
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<tr>
<td>Hindered Settling</td>
<td>Uniform size distribution of particle; bimodal size distribution of particles</td>
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<td>Packed Beds</td>
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<tr>
<td>Fluidized Beds</td>
<td>Types of fluidization (smooth, bubbling, slugging); minimum fluidization velocity, Geldart classification</td>
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<td>Elutriation</td>
<td>Freeboard; entrainment rate</td>
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<td>Solid/Liquid Separations</td>
<td>Four stages of separation; range of driving forces for separations</td>
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<tr>
<td>Selection of Solid/Liquid Separation Equipment</td>
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<td>Flow modes; stress distributions; segregation phenomena</td>
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<td>Dilute phase; dense phase; plug flow; pressure-drop calculations</td>
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<tr>
<td>Separation Efficiency (Grade Efficiency)</td>
<td>Definition; ideal versus real; sharpness of cut</td>
</tr>
<tr>
<td>Cyclones</td>
<td>Gas; liquid; collection efficiency and cut size; pressure drop</td>
</tr>
</tbody>
</table>

Table 2

#### Primary References Used in Course

- **“Storage and Flow of Solids,”** A.W. Jenike; Bulletin No. 123, Utah Engineering Experiment Station, 53(26), University of Utah (1964)

Spring 1998
The mechanics and interactions involving concentrations of particles made up the remainder of the course, which was divided into two parts. The first part covered the handling and storage of powders (design of bins, hoppers, pneumatic conveying, and gas-cyclones), and the second part of the course involved slurry handling and separations (settling, pumping, filtration, hydrocyclones, cake washing, drying, and solid/liquid separations equipment selection).

Not all of the topics could be covered in detail in the class lectures. Some of the topics were assigned as reading and homework problems. Other topics were introduced in the in-class design project, requiring the students to learn some of the material on their own.

The in-class design project we selected was the production of soda ash from the ore trona, and it spanned the last three weeks of the course. The project started with a class discussion to brainstorm and identify key processing steps. Then the class was divided into teams of two students each to size specific equipment components. One of the important learning points of the group project was that the design of any particular item of equipment in the flowsheet affects operations downstream, requiring the teams to interact in order for the designs to be compatible for the whole plant.

The out-of-class group projects give the students hands-on experience in designing and building small-scale test equipment (possibly for use in the laboratory part of the course). Two projects were sponsored by the AirMaze Corporation (Stow, Ohio) and the Dow Chemical Company (Freeport, Texas). Project A was to design a coalescence tester that measures the amount of oil removed from an air stream by a test filter media. The purpose of the apparatus was to be able to compare the coalescence efficiency of different filter media. Project B was to design and construct a liquid permeability tester that allows measurement and comparison of filter media permeabilities. These projects were selected because of the importance of filtration to solids processing, because they are of interest to the sponsors, and because the designs were not too complex and could be completed in one semester.

The project teams met about once a week to discuss design options and problems. Project A resulted in a paper design that is being considered for a research project. For Project B, the apparatus was designed and constructed as shown in Figure 1. Unfortunately, the semes-

![Figure 1. Photograph of apparatus designed to determine permeability of filter media. The apparatus controls flowrate while measuring pressure drop. It was constructed as part of an out-of-class project.](image)

| TABLE 3 |
| Possible Laboratory Equipment and Experiments |

<table>
<thead>
<tr>
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<th>EXPERIMENTS</th>
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<td>Ball mill; batch-grinding test</td>
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<td>Pressure drop; rate of conveying</td>
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<td>Mixer</td>
<td>Mixing of coarse and fine particles</td>
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<td>Segregation apparatus</td>
<td>Effects of transport and flow on segregation of well-mixed powders</td>
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<td>Hydrocyclone</td>
<td>Effects of flowrate on separation cut size, grade efficiency</td>
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<tr>
<td>Screener</td>
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<tr>
<td>Hopper</td>
<td>Mass flow and funnel flow</td>
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<td>Small-screw conveyer</td>
<td>Loading versus conveying rates</td>
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<tr>
<td>Settling test</td>
<td>Effects of concentration and additives on settling</td>
</tr>
<tr>
<td>Viscometer</td>
<td>Measure slurry viscosity as function of concentration</td>
</tr>
</tbody>
</table>
ter ended before the students could test the apparatus, but test results by two students after the end of the semester showed the apparatus performs as desired.

The class toured the Dow Chemical facility in Midland, Michigan, and were permitted to see up close the process equipment they were learning about in class. Tours such as this are valuable because they give the students a sense of the size of some of the equipment and they instill confidence when the students see processes in operation.

Future offerings of the course may include a laboratory in place of, or in combination with, the out-of-class design project. A list of equipment and possible experiments that could be included in the lab is given in Table 3.

The NSF GOALI program provided travel funds to take the students to Midland and for one of the authors (KJ) to travel from Midland to Akron to teach the students. Future funding may not be available, however; hence, travel will be scaled back and the course will have to be modified. A set of course notes have been developed that will be useful, and plant tours should be possible with industries in the local Akron area. The course may not be team-taught in the future, but companies can be supportive by encouraging their engineers to give seminars on selected topics. Other options include sending video tapes by industrial engineers to the class, or using distance learning facilities if available.

The eight undergraduate and three graduate students felt they received an exceptional experience in this course. They thought the blend of academic and industrial instructors made the class more interesting and gave it a practical application and design flavor that complemented their theoretical training. They strongly voiced their opinion that better textbooks are needed on this subject.

Asked on a course feedback questionnaire if they would recommend the course to other students, some responded

• “Yes. The class gave a valuable overview of solids processing with a lot of practical application.”
• “Yes. It provided a well-rounded look at solids processing while still covering the topic.”
• “Definitely. The topic is really fascinating because there doesn’t seem to be enough known about it.”

CONCLUSIONS

The course described here is team-taught by academia and industry and has a mix of theory and practical design in addition to lectures and hands-on experience for the students. The course is still evolving, but we feel it covers many of the important topics in solids processing that engineers need to know before going to work in today’s chemical process industries.

We were fortunate to have the support from NSF and the Dow Chemical Company that allowed one of the authors (KJ) to travel to Akron. The travel and time commitments are not practical in most cases, but the benefits to the students made the effort worthwhile enough to justify the effort to find industrial engineers in the local university communities who are willing to contribute to the course.

ACKNOWLEDGMENT

The National Science Foundation, Grant CTS-9613904, the Dow Chemical Company, and the AirMaze Corporation funded this work.

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PARTICLE SCIENCE AND TECHNOLOGY
EDUCATIONAL INITIATIVES
At the University of Florida

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The NFS Engineering Research Center (ERC) for Particle Science and Technology at the University of Florida addresses the need for students trained in particle science through interdisciplinary, multi-faceted educational initiatives. Particle Science and Technology is a term that has something for everyone. The term is so broad and the engineering disciplines in which it is relevant are so many that no single discipline can supply the resources and expertise (or room in the curriculum) to cover the field adequately. In chemical engineering alone, “particle science and technology” makes its appearance directly or indirectly in numerous contexts, such as fluidization operations, particulate separation phenomena, and colloidal and interfacial phenomena, to name a few.

The importance of particle science and technology to the practicing engineer has been articulated effectively.11,21 As Ennis, et al.,11 point out, a graduating engineer seldom sees examples of the unique problems particle-based processes pose in industry (e.g., stability of dispersions, transport of powders, granular materials or slurries, mixing of particles, and separation of liquids or solids in finely divided form dispersed in a fluid, to name a few).

As is well known now, the prevalence of particle-based processes and operations in science and industry has also brought to the forefront the role of surface and interfacial phenomena and fluid/particle (e.g., microhydrodynamics) and particle/particle interactions. Their importance has been recognized for a long time in colloid science, but their role in others areas (e.g., tribology, friction, synthesis of advanced materials, and cleaning microelectronic substrates) is no less significant. What is also important is to introduce the students to the fascinating array of modern instrumentation and analytical techniques that has emerged in recent years. For example, the development of scanning tunneling microscopy and its many offshoots has opened up possibilities heretofore unimagined (e.g., measurement of atomic forces and manipulation and imaging of atoms, molecules, and particles on surfaces). This also implies that at least some basic principles of the methods be introduced in courses so that the students can appreciate these new tools and their unexplored possibilities.

INSTRUCTIONAL MODULE SERIES

How does one make room in an already overcrowded curriculum for these materials? Where does one go for resources in specialized areas to supplement what is currently available? How does one encourage a faculty member to prepare instructional materials when universities rarely encourage, in a real and substantial manner, the preparation of textbooks or other educational aids? Is there a way to develop instructional materials that can also be used in continuing education courses in industry? Such questions have formed the motivation for development of an “Instructional Module Series Program” at the ERC.13

The instructional modules are reasonably self-contained educational aids suitable for two or three one-hour lectures on a sufficiently narrowly focused topic in particle science and technology. Each module typically includes, in addition to text and figures, worked-out examples, quizzes, end-of-the-module review questions, and annotated references. The level of the modules may vary and can be restricted to undergraduate or graduate materials or materials suitable for continuing-education courses. The last includes modules written for industrial researchers as well as those targeted to plant-level personnel.
Currently, the modules are prepared in printed form as attractive booklets, but other media may be considered in the future. We have published two modules so far\textsuperscript{[1,5]} and plans for others are underway. The table of contents of the first module is presented in Table 1. The ERC is currently recruiting potential authors from both academia and industry and will provide compensation for manuscripts accepted for publication as a module by the ERC as part of the instructional module series.

INTEGRATION OF INSTRUCTIONAL MODULES IN COURSES

The module program is meant to address a number of difficulties an instructor faces in preparing instructional material and in developing courses. Since the modules are short in length and narrowly focused in terms of topics, they require significantly less time for preparation, and faculty members and industrial scientists and engineers can afford the time needed to prepare them.

The modular form of the material also makes it easy for using the material in standard courses; if the curriculum does not permit room for new courses, at least some of the essential elements of the area can be introduced in other courses. Some examples of such possibilities are:

- The viscosity of dispersions is seldom discussed in many engineering courses, but a module on the Einstein equation for viscosity of a dilute suspension and on the Krieger-Dougherty equation for concentrated dispersions\textsuperscript{[8]} can easily be incorporated in any standard course in fluid mechanics.
- Similarly, a module on aggregation kinetics can serve as an example of how standard kinetic equations (typically taught in a course on chemical engineering kinetics) help in developing ‘population balances’ and evolution of size distribution in colloidal or aerosol dispersions.
- Undergraduate thermodynamics courses introduce the concept of second virial coefficient and illustrate its use in solution thermodynamics. But if a module on osmotic pressure, turbidity measurements, and Zimm plots\textsuperscript{[6]} is available, the thermodynamic courses can be used as vehicles to introduce a particle science example and to illustrate the use of thermodynamic concepts in the characterization of particulate systems.
- The comminution module outlined in Table 1 finds a natural place in a course on unit operations in chemical engineering as a particle science example as well as an illustration of the use of rate equations and mass-balance equations.

Of course, these are only a few of the many possibilities.

PARTICLE SCIENCE AND TECHNOLOGY COURSES

Because of the existing activities in the area of colloids and surfaces, the curriculum at the University of Florida has included for a number of years a two-credit course on interfacial phenomena, ‘Particulate Interfacial Systems: Science and Engineering.’ This course, primarily at the undergraduate level but also taken by graduate students unfamiliar with the subject, consists of a general introduction to colloids, micelles and microemulsions, colloidal and surface forces and surface tension, and related interfacial phenomena.

A more elaborate course is also under development based on a book by Hiemenz and Rajagopalan.\textsuperscript{[5]} The first chapter is designed to be sufficiently general to offer a broad introduction to particles and colloids. It also includes 21 ‘vignettes’ (about a page each) that highlight the interdisciplinary impact of particle science, colloids, and surface science and, further, illustrate their use in a broad array of applications ranging from environmental remediation and xerography to targeted drug delivery and molecular recognition. An example is shown in Table 2.

In addition, a new graduate-level course on colloid physics has been introduced into the curriculum. In contrast to conventional courses on colloids, this new course focuses on an introduction to liquid-state physics and its applications in understanding structure, phase transitions, and properties of concentrated or strongly interacting colloidal dispersions.

Courses on colloids and interfaces are relatively well established in the chemical engineering curriculum in many universities,\textsuperscript{[8]} but the same cannot be said of the somewhat more broadly defined area of ‘particle science and technol-

### TABLE 1

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<th>Contents: Instructional Module on Communion\textsuperscript{[5]}</th>
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<td>2. The relationship of size reduction to basic physics</td>
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<td>3. General approaches to grinding-equipment selection, design, analysis</td>
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<td>4. Representing particle-size distribution data</td>
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<td>5. Mechanistic size-reduction concepts</td>
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<td>- The first-order breakage hypothesis</td>
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<td>- Impact of media size and composition on breakage rate</td>
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<td>- Other factors influencing breakage rates, including rheology</td>
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<td>- Mill capacity as a function of breakage rate</td>
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<td>7. Progeny fragment distributions</td>
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<td>8. Introduction to rate mass-balance modeling</td>
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<td>9. Advantages of batch and continuous operating modes</td>
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<td>10. Practical comminution guidelines</td>
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<td>11. Types of size-reduction machines</td>
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<td>- Tumbling media mills</td>
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<td>Review Questions</td>
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<td>References</td>
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\textsuperscript{[5]} Spring 1998
Particle Science and Technology

In order to present a general overview of at least some of the topics in particle science and technology, we have introduced a new course, “Particle Science and Technology: Theory and Practice”; it carries course numbers identifying eleven engineering and science disciplines (aerospace engineering, agricultural engineering, coastal and oceanographic engineering, chemical engineering, chemistry, computer and information science, environmental engineering, materials science and engineering, mechanical engineering, microbiology, and physics), reflecting the interdisciplinary nature of both the subject and the ERC. These multiple listings allow both upper-level undergraduate and graduate students from a wide variety of departments to enroll for the class through their respective departments, thereby improving the accessibility of the class to interested students.

The course is strengthened by the fact that it is team-taught by engineering faculty and an industrial representative. The inclusion of an industrial representative in the teaching team results in a strong applications component in the course. It is taught on a level that allows students from various disciplines to learn basic concepts in particle science and technology. Student discussions of their respective research projects during the semester further enrich the interdisciplinary focus of this experience.

Course materials currently in use include course notes provided by the instructors and the instructional modules described above. A topics listing for the course is shown in Table 3. A laboratory manual, developed to supplement the lectures, includes experiments on grinding in media mills, magnetic separation, powder density, effect of chemicals on filtration, principles of solid/solid separation by flotation, zeta potential measurements, and viscosity measurements.[9]

An additional course, “Optimization, Scale-Up, and Statistical Experimental Design,” has also been developed. It teaches these topics through extensive use of particle science applications. Grinding, extractive metallurgy, powder mechanics, composite materials issues, environmental engineer-

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**TABLE 2**

Vignette on Sedimentation Field Flow Fractionation (adapted from [6])

Were it not for the never-ending, gentle tussle between gravity and diffusion, our planet would not have an atmosphere, nor would we be here to reflect upon it! The barometric equation, which describes this ‘balance of power’ between the above two well-known phenomena, is derived in most introductory physical chemistry books and is mentioned in the closing paragraph of Chapter 2. There are many more life-sustaining processes that are affected by or rely on sedimentation and diffusion, but frequently it is the more mundane ‘practical’ consequences of these phenomena that attract our attention. One such consequence is their use in physical characterization of colloidal dispersions and macromolecular solutions.

Let us highlight one such application through one member of a class of analytical separation techniques known as Field Flow Fractionation.

The name Field Flow Fractionation (abbreviated to FFF) stands for a family of techniques, invented in the 1960s, that take advantage of the response of colloids and macromolecules to electrical, thermal, flow, or centrifugal fields to produce a chromatography-type separation of the particles.[1] In a typical setup, a suitable force field is applied in a direction normal to the axis of a thin chamber that contains the dispersion. The field forces the particles against one of the walls of the chamber, and, at steady state, a concentration profile is set up in the direction of the applied field as a consequence of the differences in the responses of the various species in the dispersion to the applied field. The particles are then eluted by flowing an eluant fluid through the chamber. The fluid velocity decreases progressively from the axis toward the accumulation wall because of friction at the wall. And, as a consequence, the particles are carried along the axis at different velocities depending upon their distance from the accumulation wall. For example, the component closest to the accumulation wall lags behind the one near the center of the chamber (see Figure 1). Samples can now be eluted through a detector or collection device. The detection is usually based on changes in standard properties such as refractive index or light absorption.

One of the more advanced of the FFF techniques is the Sedimentation FFF (SdFFF) in which the applied field is a centrifugal force (see Figure 1). A typical separation achieved through SdFFF is also illustrated in Figure 1. SdFFF is suitable for species with molecular weights larger than about 10^6 and has proven to be useful for a large number of biocolloids (e.g., subcellular particles), polymers, emulsions, and natural and industrial colloids. As we shall see soon, gravitational and centrifugal sedimentation are frequently used for particle-size analysis as well as for obtaining measures of solvation and shapes of particles. Diffusion plays a much more prevalent role in numerous aspects of colloid science and is also used in particle-size analysis, as discussed in the context of dynamic light scattering in Chapter 5. The equilibrium between centrifugation and diffusion is particularly important in analytical and preparative ultracentrifuges.

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Figure 1. Sedimentation Field Flow Fractionation (SdFFF): a schematic representation of an SdFFF apparatus and of the separation of particles in the flow channel. A typical fractionation obtained through SdFFF using a polydisperse suspension of polystyrene latex spheres is also shown (adapted from Ref. 7).
ing problems, and statistical process control are some of the many particle science and technology problems that the students explore while participating in this course.

**PARTICLE SCIENCE AND TECHNOLOGY INTRODUCTORY TEXTBOOK**

The ERC recognizes the need for an introductory-level textbook to be used in a class such as described above. Therefore, a textbook is under development (*Introduction to Particle Science and Technology*, by Richard Klimpel). It is being written from the perspective that particle science and technology is a critical part of the education and training of students from a variety of engineering and scientific disciplines. Given this interdisciplinary focus, the book is being designed to be accessible to students across the wide range of disciplines and at the same time provides references that direct students to further, more specialized resources. The book will allow students with standard university-level science and mathematics backgrounds to become familiar with particle science and technology concepts in a challenging, but not technically overwhelming, introduction.

**RESEARCH-ORIENTED EDUCATIONAL PROGRAMS**

A key component of the ERC education effort is providing students with the opportunity to participate in hands-on research in particle science and technology. Since 1994, over 200 undergraduate students from 14 different departments have participated in particle science and technology research labs. These students are developing the skills necessary to work in interdisciplinary research teams and to improve their written and oral communication skills through research presentations and reports. This program supports students for multiple semesters, resulting in a solid particle research component in the education of these undergraduates.

The development of teaching materials such as the instructional module series and textbook, the addition of particle science and technology courses to the university curriculum, and enhancement of the undergraduate education experience through hands-on, team-research projects are part of the ERC commitment to improving student preparation for work in the field of particle science and technology.

**ACKNOWLEDGMENT**

The authors would like to acknowledge the financial support of the Engineering Research Center (ERC) for Particle Science and Technology at the University of Florida, the National Science Foundation NSF Grant #EEC-94-02989, and the Industrial Partners of the ERC.

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*Information on References 3-5 and 9 can be obtained by writing to Publications Coordinator, ERC for Particle Science and Technology, 418 Weil Hall, University of Florida, Gainesville, FL 32611-6155 (e-mail: erc@eng.ufl.edu).

Random Thoughts . . .

ABET CRITERIA 2000
AN EXERCISE IN ENGINEERING PROBLEM SOLVING

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In recent decades, the biggest accreditation hurdle for most of us has been persuading ABET that we were really teaching all the engineering design we claimed to be teaching. Starting in 2001, when “Engineering Criteria 2000” becomes the accreditation standard for all U.S. engineering programs, the hurdle will be a lot higher. Under the new system, for example, we will have to demonstrate that our graduates possess the skills to function on multidisciplinary teams, communicate effectively, and engage in lifelong learning, and that they understand contemporary issues, professional and ethical responsibility, and the impact of engineering solutions in a global/societal context. So far no one appears to know exactly what all of that means, but it seems clear that producing students with those characteristics will require some major changes in what we teach and how we teach it.

What makes Criteria 2000 particularly challenging—and either exciting or threatening, depending on your point of view—is its requirement of outcomes assessment. In the past, we could gain full accreditation simply by showing that we were teaching the required amount of mathematics, chemistry, design, etc. We will still have to do that when the new system is in force, but now we will also have to demonstrate how well students are learning the prescribed content and skills. Moreover, we will have to satisfy our ABET visitors that we have in place a process to modify our curricula if any required learning outcomes fail to meet the new criteria.

In other words, engineering curricula are now like open-loop process systems, but starting in 2001 they will have to function as closed-loop feedback-controlled systems. The difference between these two modes of operation is as profound as it is in manufacturing processes, only the difficulties of designing and implementing an optimal control scheme in an education context are greater. The contrasts are shown in Table 1.

Table 1 is not intended to suggest that control of manufacturing systems is easy, but rather that it is much easier than control of educational systems. Deciding what you want a manufacturing process control system to accomplish, designing and implementing the system, and determining how well it works once it is in place are all relatively straightforward exercises. In an educational system, little is straightforward. Desired outcomes tend to be either vague or controversial; the effects of system changes on learning outcomes are difficult to assess unambiguously (there are always several possible causes for any observed effect); and both the costs of the changes and the benefits of the outcomes are endlessly arguable. Furthermore, few industrialists would argue against attempting to improve product quality or rate of return on investment, but any proposed change in curriculum structure or instructional methods faces almost certain opposition from some faculty members and administrators.

As engineering departments begin to face the prospect of confronting these difficulties, they will seek answers to several questions:

1. What data must be collected to assess the required skills? Results of standardized tests? Videotaped oral presentations? Multi-year student portfolios? Must assessment data be collected for all students, or only a representative sample? If the latter, how big should the sample be, and how should it be chosen?

2. Who should evaluate the student products in light of the accreditation criteria? The students’ course instructors? One or more additional faculty members? Should training be provided to evaluators to ensure interrater reliability? Who should provide it?
3. What percentage of students in the sample population must satisfy each criterion? What percentage of the criteria must be satisfied for a department to qualify for full accreditation?

4. Will it be enough for a department to show that it is doing something—anything—to take assessment results into account in curriculum and instructional planning, or will the effectiveness of corrective measures be evaluated as well? What criteria will be used to evaluate them?

All of us will be seeking answers to these questions in the next few years, and answers will certainly be found. Producing graduates with the specified characteristics and proving that we have done it may be an extremely tough optimal control problem, but engineers are used to solving tough problems and we'll eventually solve this one too.

From now until 2001, departments applying for accreditation may choose whether to go by the old or the new criteria, and thereafter the new criteria will be used exclusively. Some departments acknowledge that the change is inevitable and are wisely starting to modify their instructional programs in anticipation and to assess the learning outcomes. Others are choosing to ignore the whole thing, perhaps hoping that it will go away. It probably won't. In recent years industry and funding agencies like the NSF have increasingly called for changes along the lines of the new criteria, and departments who discount the new requirements may be in for a rude surprise when their ratings come in.

Or they may not be. Perhaps the most important question about the new system is,

5. How serious will ABET be about Engineering Criteria 2000?

Several departments have already been evaluated under Criteria 2000 and have received full accreditation, but ABET may not be strictly enforcing the new criteria in this pilot stage. For example, one of these departments argued that its faculty's involvement in multidisciplinary research was sufficient to demonstrate that its students were equipped to work in multidisciplinary teams, and the ABET visitor apparently bought this argument. Granted, it may be reasonable for ABET to go easy on volunteer departments now in exchange for the opportunity to test-drive the new system. If such arguments are accepted after 2001, however, there is little chance that Criteria 2000 will be taken seriously enough to accomplish its intended reform of undergraduate engineering education. On the other hand, if ABET puts teeth into its requirements, and one or two prominent departments fail to meet the new criteria and are denied six-year accreditation, reform will almost surely take place. All of us will be watching attentively for signs of how the drama will play out. It promises to be an interesting three years.

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/
OUTCOMES ASSESSMENT METHODS

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All chemical engineering departments are now, or soon will be, developing and implementing outcomes assessment plans in order to satisfy ABET Engineering Criteria 2000 (EC 2000). For many departments, this will require a paradigm shift in the administration of the undergraduate curriculum. Among the aspects that may disappear are impersonal lectures delivered by aloof faculty who teach their course in isolation from the rest of the curriculum. Among the aspects that may appear are faculty who regularly communicate with each other about course content, the goals of the undergraduate curriculum, whether these goals are being achieved, and what needs to be done to be certain that the goals continue to be achieved.

Outcomes assessment is a method for determining whether students are learning and retaining the information and skills they need for success in their chosen field. To perform outcomes assessment, measures of this information and these skills are needed. In the traditional curriculum, illustrated in Figure 1, the output of the educational process is assumed based upon the content of the curriculum and the "quality" of the faculty. With no measures of the output, this is analogous to feed-forward control, in which the output is dependent on the accuracy of the model used to predict it, in this case, the curriculum and faculty teaching ability. In the curriculum with a strong assessment component, illustrated in Figure 2, the output of the educational process is measured and compared to the set point (goals), and deviations from the set point are corrected via feedback to the curriculum. This is analogous to feedback control. As shown in Figure 2, there may be multiple measurement and feedback points, analogous to cascade control.

Assessment may be summative or formative. Summative assessment (usually just called assessment) is conducted for the purpose of making a final (summative) judgment about the effectiveness of the educational process. It may be used by an institution to make decisions about global learning outcomes, resource allocation, and accountability. Such assessment is usually a formal process and consists of documentation showing that students completing degree programs have the knowledge and/or skills required of their degree program in addition to a global set of skills expected of all college graduates. The audience for summative assessment is usually external to the department or university.

Formative assessment (often called classroom assessment) is conducted for the specific process of improving (forming or re-forming) the educational process and usually begins before the educational process is completed. It may involve continuous, often informal, assessment of student learning with the expressed purpose of improving teaching and learning within a specific course or curriculum. The audience for formative assessment is usually within a department or is the instructor in a specific class. The elements of classroom assessment are described in more detail elsewhere. Effective assessment plans have both summative and formative aspects, so external constituencies can be satisfied while continuously improving the educational process.

This paper is an introduction to the process of developing...
an outcomes assessment plan. There are numerous citations to functioning assessment plans. A more detailed background on outcomes assessment, the details of one assessment plan, and a more extensive bibliography are available,[14] and a more detailed guide to developing an assessment plan is also available.[13]

An outcomes assessment plan consists of three components:

1. **Goals**, which define what is expected of students (the set point)
2. **Measures of achievement of these goals**, multiple measures being best (comparison of outputs to the set point)
3. **Feedback to correct and to improve the educational process** (the feedback loop)

These three components are discussed in sequence below.

**GOALS**

To develop an assessment plan, educational goals must be defined. It is necessary to elucidate the knowledge and skills students should possess upon completion of a degree program. EC 2000 suggests eleven goals;[15] however, many of them leave ample room for interpretation. The result may be a different set of acceptable goals for departments with different objectives (i.e., preparation for academic career, preparation for industrial career). The goals for the Department of Chemical Engineering at West Virginia University, developed prior to the EC 2000 goals, are one example of goals developed by faculty consensus.[16]

Definition of goals may be a difficult process for faculty members unaccustomed to discussing undergraduate educational issues. It is likely that individual faculty members have very different ideas. For example, a course in fluid mechanics can differ considerably when taught by different instructors. In one case, the course may be mostly theory; in another case, it may be mostly practical; and in a third case, it can be a mixture of theory and practice. The differences stem from the variant opinions faculty have of the goals of the undergraduate educational process. There are no easy solutions to this problem. Faculty must be prepared for a vigorous dialog, they must recognize that there are opposing opinions, and they should be ready to compromise. The EC 2000 goals are a good fall-back position for departments unable to achieve consensus on more specific goals.

**MEASURES**

There are several proven assessment measures, but it is likely that as more departments develop assessment plans, new measures will be developed. Seven established assessment measures are discussed here.

**Testing** • This is the simplest measure and is completely summative. Standardized assessment tests have been developed for many non-engineering curricula. In engineering, the FE exam can be used, as could the GRE engineering test. With recent changes making half of the FE exam discipline specific, it is now a better measure of discipline-specific knowledge than the GRE. An advantage of testing is that outcomes can be compared to national norms, which is often what legislatures and boards of trustees want. A disadvantage of testing is that feedback is difficult to obtain from the FE exam. Students taking it in the spring do not get results until after they graduate, and information on what topics students demonstrated strength or weakness is not easily obtainable. If testing is to be used, it should be one of several measures rather than the only measure, since feedback is an essential component of a quality outcomes-assessment plan. The University of Tennessee system[6,7] uses the FE exam as the basis for an assessment plan, and the University of Missouri, Rolla, uses the FE exam as a component of an assessment plan.[8]

**Portfolios** • The Colorado School of Mines has used a portfolio-based assessment plan for over a decade.[9] Longitudinal records for a statistically significant random sample of students are maintained. These records are similar to ABET portfolios for a class except that they are for an individual student and cover the student’s entire tenure at the university. The idea is that student accomplishments in assignments and projects demonstrate achievement of goals (much like an artist’s, model’s, or photographer’s portfolio). In every class, coursework that demonstrates students’ abilities pertinent to the stated educational goals is identified and added to the portfolio. Some advantages of a portfolio-based assessment plan are that it does not intrude on routine classroom activities and multiple examples of a student’s work that demonstrate skill development and/or improvement are included. Some difficulties are the need for correct analytical methods to identify a statistically significant sample of students and the need to remind all instructors of selected students to collect appropriate portfolio material.

**Capstone Experiences** • Since all chemical engineering
programs have a capstone experience that draws on material learned earlier in the curriculum, they are a rich opportunity for outcomes assessment. For example, in our department, students are required to do a series of individual projects and to defend their work in front of two faculty members.\[^{[9,10]}\] (This requirement has existed in our department for over twenty years.) They must work alone, although they may "purchase" consulting time from the instructor for a small, time-dependent grade deduction. This requires well-formulated questions that can be asked and answered quickly (the questions are recorded because they also provide assessment information). The defense serves multiple purposes: it is both an assessment mechanism and a tutorial for the student. Issues common to a significant number of students are brought to the attention of the faculty and are emphasized in the project review in class. Our students have a love-hate relationship with these projects; they hate the pressure, but they recognize the quality of the learning experience. Given the faculty time involved and the potential for student revolution if they were added to a curriculum without a culture supporting them, these individual projects are not recommended as an assessment measure. However, aspects of the projects can be borrowed.

The key advantage of the individual projects is that the work presented by the students and their responses to questions allow the faculty to understand the student's thought patterns and to identify any concepts that are not fully understood. This can also be accomplished in other ways. What is needed is all of the information students are told to omit from final reports: what they tried that did not work and/or what misconceptions they corrected while doing the project. One method is for groups of students to do a series of projects similar to the individual projects described above, with faculty directing questions to specific students.

Students could also be asked to keep a diary of what they did, alternatives they considered, and dead-ends they encountered (diaries are a well-known classroom assessment method\[^{[11]}\]). This diary could be submitted weekly or periodically during the semester for evaluation by the instructor from an assessment perspective (not for a grade). The purpose of keeping the diary should be explained to the students so they will take the assignment seriously.

The nature and scope of questions asked during a capstone experience can also yield valuable assessment information. We keep track of the questions asked during "consulting" on the individual projects. For a group project, a periodic, formalized question-and-answer session for each group should yield useful information about the level of student understanding and on their misconceptions. An interim presentation (or two) or periodic meetings with a mentor and/or a TA, in which the interaction was documented in detail, could yield the same information. If some form of individual assessment were desired, students could be required to work on the project for a week or two, outlining a solution strategy and generating questions. Then, after these preliminary strategies and questions were assessed, the group project could begin.

There are no doubt other ways in which capstone experiences can be adapted as assessment measures. When confronted with developing an assessment plan, the first place to consider should be the current curriculum and how it can be adapted to become part of an assessment plan. Since all curricula have a capstone design experience, it is a good place to start an assessment plan.

**Questionnaires** • Questionnaires are a common assessment measure. Typically, they are sent to employers and to alumni a few years after graduation. They have also been used at the end of each academic year.\[^{[12]}\] Questionnaires to alumni give us feedback on their preparation for employment, and questionnaires to employers provide feedback from their perspective. Questionnaires for students in the curriculum are useful for improving the quality of student "life" within the curriculum.

In all cases, student and alumni beliefs about what they learned is being measured. Asking the right questions is important. We ask alumni and employers about global skills such as the ability to communicate and to work in teams, for self-education, etc. We also ask students at all levels what they believe to be the most important thing they learned (the answers may be surprising to some because they tend to focus on communication skills, time management, etc., while fluid mechanics, thermodynamics, or separations are rarely cited!).

One advantage of questionnaires is that it is an anonymous method of obtaining feedback. There are several disadvantages, however. The return rate of alumni questionnaires tends to be low, between 25-33%. Having the questionnaires completed by phone would increase the rate of return, but might be annoying to alumni. Our return rate on employer questionnaires has dropped to zero in the five years we have been using them, with privacy issues (even though the questionnaire does not identify the student) most often cited. Since EC 2000 suggests employer feedback as an important measure, this issue will have to be addressed in the future.

**Interviews** • Another assessment measure is student interviews, both individual and group. Our chairman interviews each class as a group at the end of each academic year, and random groups of students meet with our Industrial Visiting Committee. Since some students do not like to speak up in a group, individual interviews with randomly selected students could also be used. The information obtained from these interviews is very similar to that obtained from the questionnaires in that the quality of the students' life, and their self-evaluation about
what they have learned is what is measured.

**Job Placement** • Records of job placement are a valid assessment tool since they measure the demand for graduates from a program, and high demand usually means high-quality graduates. Most departments should have easy access to this information through their career services or placement offices. In recent years, many of our students have obtained positions without going through our career services center, so the department also maintains placement records. A disadvantage of job-placement records as an assessment measure is that employment opportunities can be affected by economic conditions unrelated to the quality or success of an undergraduate program. Therefore, while job-placement information is one outcomes measure, it is a good example of why multiple outcomes measures are needed.

**Classroom Assessment** • In classroom assessment, an instructor measures student learning more frequently than by traditional testing, often on an informal basis. The goal is to determine whether a particular lecture or exercise was successful. Classroom assessment is not new, and the definitive work on the subject contains fifty classroom assessment techniques.[2] They include methods for assessing critical-thinking skills, problem-solving skills, synthesis and creativity skills, and student attitudes. Perhaps the most widely known classroom assessment technique is the “minute paper” where students take the last minute of a lecture to write down what they learned in that class; the instructor then uses this informal feedback to assess the success of that lecture period. A variation of this is the “muddiest point,” where students write down the item they found the most confusing in a given lecture.

Classroom assessment is purely formative. Alone, it will not satisfy an external constituency, although it should be a part of an assessment plan that improves student learning. Examples of classroom assessment techniques that I have used successfully are presented elsewhere.[11]

The seven assessment measures above are among those most commonly used. Clearly, they are imprecise measures of learning outcomes. The lesson is that a valid assessment plan must include more than one or two of these measures; however, all seven need not be included to have a quality assessment plan.

**FEEDBACK**

One purpose for outcomes assessment is continuous program improvement. Feedback is absolutely essential to the process. As shown in Figure 2, a quality assessment plan has many nested feedback loops. Feedback is taken from alumni, graduates, students in the program, and students in a class, and it occurs at multiple points within the curriculum. In our curriculum, a report is generated from the results of each individual design project and is circulated to all faculty, who take it quite seriously. The results are discussed at a faculty meeting if it is deemed necessary.

Completing the feedback loop requires the same paradigm shift in faculty attitudes as does development of program goals. For there to be continuous program improvement, faculty must be willing to accept feedback. No one likes to hear that students have a significant knowledge gap in material covered in their class, but when it occurs, what is the response? Does the instructor ignore the feedback? Does the instructor attack the assessment process? Does the instructor examine how the class is taught, trying to determine why there are knowledge gaps and attempting to rectify the situation? When feedback from alumni suggests that oral and written communication skills need improvement, are faculty willing to modify the curriculum to include more communication exercises?

**DISCUSSION**

It is clear that implementation of an outcomes assessment plan requires more attention to be focused on the results of the teaching and learning processes instead of solely on curriculum content. How this plays out is yet to be determined. It is unclear what will occur if it is determined that outcomes assessment requires devoting a little more time to undergraduate teaching and a little less time to research. Perhaps some departments will decide they need to employ a full-time educator to coordinate assessment, to oversee evaluation of the curriculum as a whole, and to ensure desirable outcomes.

It takes several years to implement an assessment plan. Trying to implement an assessment plan over the same one-year time scale needed to prepare for an ABET visit under the old guidelines will yield unsatisfactory results. There is a hidden challenge with EC 2000. On the surface, it may create the illusion of being easier to satisfy than the Engineering Topics Criteria because the specific course requirements are less proscribed. But this is just an illusion. It is much easier to create a feed-forward model (as in Figure 1) to satisfy the Engineering Topics Criteria than to create a feedback model (as in Figure 2) to satisfy EC 2000. This is partly due to the non-quantitative aspects of outcomes assessment. Even though the old requirements were criticized for their “bean-counting” aspects, many may ultimately pre-

Continued on page 145.
THE LEBLANC SODA PROCESS
A Gothic Tale for Freshman Engineers

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What principles of chemical engineering can we teach freshmen, and how should those principles be taught? The traditional undergraduate curriculum demands extensive prerequisites before students begin the quantitative study of chemical processes, typically including two semesters of general chemistry, a semester of physics, and a year of calculus. The introductory chemical engineering course arrives only in the sophomore year, so students have no clear picture of the field until their first year has passed by.

In the College of Engineering at UMass, we have revised the freshman curriculum to include overview courses from each of our departments. In addition to helping the students understand the differences between engineering disciplines and the sciences, enabling them to make an informed choice of major, these courses have other important goals. They are intended to give the students an introduction to the relationship between design and manufacturing, experience in a team project, and instruction in oral and written presentation, computational skills, safety, and engineering ethics. This is a full plate of diverse topics, and the chemical engineering principles we teach in such a course must be linked to some strong, unifying thread lest they be perceived as disjointed and scattered scraps.

We decided to devote a module of lectures in our first-semester freshman course to tracing the history of one particular process, and to use this process to illustrate and explain basic engineering principles. We wanted to choose an old process, one born before the invention of chemical engineering, so we could point to the many sad consequences of ignorance and discuss their remedies. We also wanted a process that had struggled to maturity despite innate limitations, but that ultimately died at the hands of a better-designed and more efficient successor.

The best case study of this kind that we have found is the Leblanc soda process. For the eighty years between 1820 and 1900, the Leblanc process was a pillar of the CPI; but it was so completely supplanted by the Solvay process after World War I that it is almost forgotten by modern chemical engineers. Because of its former importance, however, it has been extensively described by historians of technology, and a number of excellent accounts are available in the literature.\[1-9\]

In the following four sections of this article, we tell the story of the rise and fall of the Leblanc process and emphasize the lessons to be learned from its story. The final section describes how the material is integrated into our freshman course.

BEGINNINGS

During the eighteenth century, the production of chemicals and materials across Europe began to increase steadily under the pressures of increasing population growth and trade, urbanization, a rising standard of living, and the accumulation of capital. As demand increased, natural sources of raw materials began to fall into short supply. Among the most heavily stressed resources were soda ash (Na₂CO₃) and potash (K₂CO₃), known collectively as alkali.

Leblanc was essential to three rapidly growing industries: it was used in textile processing as an alkaline scour in the
bleaching of linen and cotton cloth; it was used in glassmaking as a fluxing ingredient to lower the melting point of soda-lime glass compositions; and in soapmaking, alkali was treated on-site with lime to produce caustic (NaOH or KOH) for the saponification of fats and oils to hard or soft soap.

The traditional source of natural alkali was the ash that remained after burning plant matter. Seashore plants were used where soda rather than potash was required, since these have the highest ratio of sodium-to-potassium content. Most popular were kelp from Scotland and barilla (saltwort) from Spain. The soda content of these ashes was comparatively small (10 to 30%) and was very variable; more seriously, supply was prone to sudden interruption by wars, tariff barriers, and acts of God.

The importance of an artificial source of soda became apparent early, and between 1730 and 1790 a dozen such processes were proposed, including a 1769 effort by the unexpected team of James Watt and Joseph Black.[1]

Half a dozen of these processes were brought to small-scale production, typically to make captive soda for an adjoining glassworks or soap works, but none proved to be competitive with natural sources. In 1783, the French Academy of Sciences offered one of its celebrated prizes for a viable process to produce soda from common salt, but that prize was never awarded.

It was in France, however, that the first truly economic process for artificial soda was born.[2] Its inventor was Nicolas Leblanc, an amateur chemist who was the personal surgeon to the Duc d’Orléans. In 1789, Leblanc conceived a two-step reaction pathway to convert common salt to soda. Leblanc left no clear record of his reasoning, although there is evidence that he might have been inspired by a false analogy with the smelting of iron from its ore. A simple block flowsheet is shown in Figure 1.

The first reaction step

\[ 2\text{NaCl} + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + 2\text{HCl} \] (batch) (1)

was well known long before Leblanc. It was the second reaction step, the production of soda from saltcake (\(\text{Na}_2\text{SO}_4\)) that was novel.

In a solid-state batch reaction carried out in a furnace, Leblanc roasted 1 part saltcake by weight with 1 part chalk or crushed limestone and 1/2 part coal or charcoal. The chemistry of this reaction step was poorly understood for a century after its introduction into industrial practice, and there are certainly many side reactions. In simplest modern terms, however, the primary reaction can be thought of as

\[ \text{Na}_2\text{SO}_4 + \text{CaCO}_3 + 2\text{C} \rightarrow \text{Na}_2\text{CO}_3 + \text{CaS} + 2\text{CO}_2 \] (batch) (2)

The product, a vile-smelling mass called “black ash,” contained soda, CaS, byproducts, and unconverted reactants. The ash was broken up and extracted with hot water, or “lixiviated”; the extract was evaporated to yield crude soda. The insoluble solids, or “tank waste,” were discarded. If reactions (1) and (2) went to completion stoichiometrically without side reactions, 1 pound of soda could be produced from 3.2 pounds of reactants; but in practice, because of the excess of CaCO₃ and carbon, impurities in the reactants, the incompleteness of reaction, and the weakness of available \(\text{H}_2\text{SO}_4\), it could require as much as 10 to 12 pounds of reactants to make a single pound of soda.[3]

Even so, Leblanc’s process was better than its contemporary competitors. Leblanc was granted a fifteen-year patent by the French government in 1791, and in the same year he formed a company to produce artificial soda, bankrolled by his patron the Duke.

A small plant was built at St. Denis on the Seine near Paris. For two years the plant operated with some success (although well below its theoretical capacity), but in 1793, the economic and political climate turned sour. France executed Louis XVI and was soon at war with the rest of Europe. All available supplies of sulfur and saltpeter (\(\text{KNO}_3\)) were requisitioned for the manufacture of gunpowder. Both of these chemicals were needed to produce sulfuric acid, and as the supply disappeared, Leblanc’s plant shut down for lack of raw materials. Worse still, the Duc D’Orléans was guillotined in November, and his assets were confiscated, including the soda factory at St. Denis that he had capitalized.
The revolutionary government was short of soda as well as every other industrial chemical, since its foreign sources had been cut off by the conflict. In order to stimulate production, in 1794 a government commission published and publicized a report on all available methods of making soda, including Leblanc’s process. His patent, which had been closely held, became widely known and began to be used in a small way by others in France and abroad—without licensing fees. Leblanc spent nearly eight years suing for ownership of the idle plant and petitioning for reimbursement for his perceived loss of patent rights. He finally regained control of the plant in 1801, but he was unable to raise the money to operate it effectively. He went into debt, grew depressed, and committed suicide in 1806.

Soon afterward, France remitted its tax on salt and restricted the import of foreign barilla, and the Leblanc process became profitable on a significant scale. A number of Leblanc works were opened, primarily near Marseilles, the center of the French soap industry. The mature development of the process, however, took place across the Channel in Britain.

**Maturity**

The Leblanc process had been worked in England in a minor way as early as 1802, but its expansion to a major industry had to wait for a drop in the price of its raw materials and the rise of a new class of chemical entrepreneurs. These factors came together in the early 1820s in three great seaports and industrial centers: Liverpool, on the Mersey; Newcastle, on the Tyne; and Glasgow, on the Clyde.

The growth of the lead-chamber process for the production of sulfuric acid in the previous three decades had dropped the price of acid from £35/ton in 1790 to £3/ton in the 1820s. Salt also became much cheaper because of changes in tax policy. In the aftermath of the Napoleonic wars, the impoverished British government had imposed a crushing £30/ton tax on salt to raise its revenues; this was finally lifted after 1823. That same year, the Anglo-Irish entrepreneur James Muspratt opened a Leblanc soda works in Liverpool, followed by additional plants in smaller towns farther up the Mersey.

Muspratt chose his site carefully in that era of expensive transportation. Transport on the roads of the time was slow, expensive, and uncertain, particularly in the wet weather of winter and spring, and the railroad would not come to the region for another decade. The only affordable transportation for raw materials was by water; this was provided by the Mersey itself, its navigable tributaries, and the network of canals that had been dug since 1757. Merseyside plants had access to coal from South Lancashire and salt and limestone from Cheshire, within twenty miles; limestone was also often carried into port as ships’ ballast and sold off cheaply at the quay.

Muspratt’s markets, like his raw materials, were nearby. Liverpool was already a center of glass works and soap manufacture. The new soda was marketed aggressively, and the plant was soon a thriving concern. Other plants opened in Britain, primarily at the three great northern seaports, and Leblanc soda began to capture the soda market away from natural sources. By 1862, the industry employed 10,000 men directly and another 20,000 indirectly in mining and transportation; that year it consumed 250,000 tons of salt and produced £2,500,000 worth of products.

In histories of the chemical industry, the Leblanc process is sometimes called a “nearly perfect” process that changed very little except for “mechanical” improvements over its history. A glance at Eqs. (1) and (2) shows that this is nonsense. Apart from the fact that the Leblanc process did produce soda, it was a recipe for turning raw materials into toxic waste. All the potentially valuable chlorine liberated from salt was vented as HCl; the sulfur that had been expensively converted to sulfuric acid was entirely lost as insoluble sulfide. These wastes caused serious problems for both the community and the manufacturers.

The first Leblanc plants were surrounded closely by residential areas, agricultural land, and rural estates. As production increased, HCl emissions from the plants burned the vegetation of the surrounding countryside and damaged stone buildings.

Scolding letters appeared in the newspapers as early as 1827, and in 1831, Muspratt was served with the first of many civil lawsuits claiming damages. This was a serious matter; the copper smelters in Liverpool had already been declared a public nuisance and had been forced out of town because of their SO₂ emissions.

The first solution tried by the soda manufacturers was to discharge the HCl through a taller stack, relying on greater dilution of the exhaust plume before it contacted the ground (the solution to pollution is dilution). The record height appears to have been 454 feet. Often, however, the result
of taller stacks was simply drawing lawsuits from acid rain
damage further downwind.

Tall stacks also did not improve the condition of workers
in the plant. The HCl fumes reportedly burned their clothes
and rotted their teeth, and it was not unusual for workers to
faint and be dragged outside to revive. Bronchitis and lung
disease were endemic. Workers over forty years old were
past their prime and were often moved out of the plant to
lighter work in the yard.

The CaS waste was also a problem. Landfilling was not
possible since there was no heavy earth-moving equipment
at that time. Tank waste was simply piled on surrounding
land, in heaps as high as 50 feet tall, many acres in extent.
Four and a half million tons of tank waste had been laid
down by 1885 in Lancashire alone. When the land had to
be leased from other owners, the cost could run as high as £1500/
acre; this was thirty times a workingman’s annual wage.

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In the acid environment surrounding the plants, the waste
piles and waterways became inadvertent chemical reactors,
producing hydrogen sulfide gas from the reaction

\[ 2\text{HCl} + \text{CaS} \rightarrow \text{CaCl}_2 + \text{H}_2\text{S} \uparrow \]  

The stench was shocking, even to the robust noses of the
Victorians.

Over the long history of the Leblanc process, as basic
chemical engineering principles were slowly formulated and
implemented, these serious economic and environmental
problems were ameliorated or eliminated, one by one.

In 1836, William Gossage, an energetic inventor and owner
of a Leblanc works, devised a solution to the problem of HCl
emissions. He owned a derelict windmill near his plant; he
packed the mill with brush and twigs, piped in water at the top
from a nearby brook, and absorbed the HCl into solution.

This was the first use of a scrubbing tower in the CPI.

The windmill was soon replaced by a patented tower of
tar-soaked stone, packed with coke or broken brick. The
Gossage tower greatly reduced gaseous HCl emissions, although
they were not completely eliminated. In particular, back-pressure from the tower reduced the rate of saltcake
production, and since workers were paid bonuses according
to output, there was a temptation to bypass the tower and
vent HCl directly when nobody was looking (an early
demonstration that it is a bad idea to give personnel an
economic or psychological incentive to do the wrong thing).
Many alkali works did not install Gossage towers at all,
preferring to pay occasional damages in court rather than to
invest in the capital costs.

In 1863, pressure from the rural gentry forced Parliament
to pass the first Alkali Act, which mandated that plants must
scrub 95% of the HCl from their stack gases. A network of
inspectors was established to enforce the Act by regular
visits and surprise inspections. One of the first alkali inspectors
was George E. Davis; his experience inspecting chemical
works led him to formulate the first comprehensive view
of chemical engineering as a discipline, culminating in his
Handbook of Chemical Engineering (1901 and 1904).

The weak HCl solution condensed by Gossage towers had
little market at the time, so the first result of HCl scrubbing
was to convert the gas-disposal problem into a liquid-disposal problem (illustrating the dictum that the chief cause of
problems is solutions). Most of the liquid HCl was expelled
into nearby canals and brooks. The Sankey Canal on Merseyside became so acidic that iron-bottomed barges were
kept off it for fear of corrosion.

As the understanding of basic chemistry improved through
the nineteenth century, auxiliary processes were gradually
developed to convert the Leblanc wastes into saleable
byproducts or recyclable raw materials. The most important
were two processes that transformed the HCl from saltcake
furnaces into Cl\textsubscript{2}: Weldon’s process (1867) used a reaction
with manganese dioxide, while the Deacon-Hurter process
(1872) used a copper chloride catalyst. The Cl\textsubscript{2} was abso-

The bleaching powder works were hardly perfect by modern standards. The reaction was carried out batchwise in
large chambers, and the finished powder was shoveled out
manually by workers smeared with beef tallow, wearing
goggles and dampened cloth masks called “muzzles.” Never-
theless, this was one of the first major successes at con-
verting an industrial waste into a valuable byproduct.

In 1887, Chance developed a process to recover sulfur
from black-ash waste, and the solid-waste problem was also
alleviated. From the 1840s onward, sulfur burning was re-
placed by the roasting of pyrite ores to produce H\textsubscript{2}SO\textsubscript{4} for
the saltcake process; the pyrite slags were processed to re-

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Spring 1998
cover iron and copper as further byproducts.\[^{[5]}\]

Several mechanical improvements were also made over the latter half of the century. Leblanc black-ash furnaces were originally mixed by hand throughout the course of the reaction, a labor-intensive and inefficient technique. In 1853, Elliott and Russell developed a revolving furnace that mixed the reacting solids much more effectively. These “revolvers” came into general use over the following fifteen years.

In 1861, James Shanks perfected a method for extracting the carbonate from black ash using an ingenious system of vats that reduced manual handling of the material, and this improvement was also generally adopted. Large Leblanc works often attempted to exploit economies of scale, but this was not always successful. Thermodynamics was in its infancy at the time, and there was no understanding of the principles of heat and mass transfer, so large furnaces and towers were often improperly sized or proportioned.\[^{[1]}\]

By the late 1880s, the Leblanc process had been modified to recover the bulk of its wastes and to operate far more efficiently than it had done originally. The process was finally mature; but it was also obsolete.

**DECLINE**

As early as 1811, it was known that sodium bicarbonate could be precipitated from a brine solution saturated with ammonia and \( \text{CO}_2 \). The reaction was easy to carry out on the benchtop, but despite repeated efforts, no one was able to make it a viable industrial process. The sticking point was the loss of ammonia. In order to make an ammonia-soda process economical, almost all the ammonia had to be recovered and recycled, and the gas-handling systems of the day were not equal to the job.

Finally, in 1861, after a long period of R&D, Ernest Solvay constructed a practical plant. Solvay’s process was licensed in Britain by Ludwig Mond, who made further improvements, and Brunner, Mond & Co. began to produce soda by the Solvay process at Winnington, on the Merseyside, in 1874.

Leblanc soda was an inherently batch process, and it carried all the natural disadvantages of batchwise production in the manufacture of a large-volume commodity chemical. It required a lot of manual labor; uniform product quality was hard to maintain between batches; and there were few opportunities for thermal recycle, so a great deal of energy was wasted.

The Solvay process, on the other hand, was continuous. It emitted no \( \text{HCl} \), and its solid waste was the chloride of calcium, much less objectionable environmentally than the sulfide. Solvay’s process also had a simpler separation step (filtration rather than extraction). Mond did not try to undercut the prices of Leblanc manufacturers since demand for soda was high and he could sell all his product without a price war. Nevertheless, as the capacity of the industry grew, the price of soda slid from £4 10 s per ton in 1861 to £2 15 s in 1889.\[^{[8]}\] Solvay plants were still profitable at this price, but Leblanc manufacturers were soon selling their soda at a loss. They stayed afloat only through the profits from bleaching powder, which now became their principal product.

The Leblanc manufacturers formed a voluntary Bleaching Powder Association in 1883, a cartel that propped up the price of bleach artificially by limiting production (this was not illegal at the time, although it was frowned upon in many newspaper editorials). Inevitably, the cartel collapsed in 1889 through price undercutting by nonmembers and renegade member companies. During this period, chlorine was also beginning to be produced in quantity electrolytically, and the Leblanc monopoly on bleach was disappearing.

It became clear that a voluntary association would not be able to enforce prices and keep the industry viable. Finally, in 1890, the forty-five remaining Leblanc works in Britain merged to form United Alkali, a consolidated, publicly-held stock company. The new company closed the most inefficient plants, downsized the industry, and diversified its product lines.

The Leblanc process staggered on in Britain, in increasingly straitened circumstances, for another thirty years; but the last Leblanc works closed soon after World War I. United Alkali itself was swallowed up in the giant merger that created Imperial Chemical Industries in 1926.\[^{[9]}\]

**LESSONS**

By tracing the rise and fall of the Leblanc soda process, we can introduce a surprisingly large number of elementary chemical engineering principles at a level that doesn’t require much pre-existing background in chemistry and physics. For example:

- The concepts of a process, its flowsheet, and the unit operations arise naturally in explaining how the reaction scheme of Eqs. (1) and (2) was translated into practice. Only a few simple inorganic reactions are necessary, and the students become more comfortable with these over the course of the semester as they concurrently study their first semester of college chemistry.

- The Leblanc process offers many concrete examples of how the economic potential of a process is affected by the supply of raw materials, the demand for product, transportation costs, plant-siting decisions, and government regulation and tax policy.

- The advantages and disadvantages of batch vs. continuous processes are illustrated by the final struggle of Leblanc’s process with Solvay’s.

- The health, safety, and environmental problems associated with the process give a backdrop for discussions of plant safety and engineering ethics later in the course.

The Leblanc process offers such a rich context that an
The course is typically taught in two sections averaging thirty students each. In the paragraphs above, we gave a condensed and sequential account of the Leblanc process. In practice, this material is spread across a four- to five-period block of lectures. At each opportunity to illustrate a new concept (classification of processes, economies of scale, etc.), we suspend the narrative and focus on a discussion of that concept, involving the students in as much back-and-forth interaction as possible. Then the narrative resumes.

Although we present a good deal of concrete detail and history in these lectures, the emphasis is not on memorization of detail, as it might have been in an old-style industrial chemistry course; instead, it is to illustrate and illuminate basic principles within one coherent story. The students apply these principles to other processes in weekly homework assignments and in the two examinations that are given during the semester.

At the beginning of the course, the students are organized into teams of three, with each team assigned a different commodity chemical process to research in the literature. During the semester, each team gives two oral presentations on its process to the class and produces a final written report. Our in-depth discussion of Leblanc soda helps the students organize a clear presentation of their own team’s process and its flowsheet. By the end of the term, each student has actively participated in analyzing and presenting one simple chemical process and has seen analogous presentations on the nine or ten different processes studied by the other teams.

More details of the syllabus, structure, and lecture schedule of our freshman course can be found on the web at

http://www.ecs.umass.edu/che/classroom.html

This web site will be expanded and updated as the course evolves.

Does the strange, Gothic tale of Leblanc soda scare freshmen away from chemical engineering? Does it give them the impression that they are entering a demented and immoral profession? That hasn’t been our experience at all. After recounting each of the inefficient or damaging aspects of the Leblanc process, we can turn to the class and ask, “Now, why did they have this terrible problem?” and the students quickly recognize that the correct answer is, “Because they had no chemical engineers.” Students are eager to solve real problems, and the Leblanc history offers an abundance.

All too often, the first experience of chemical engineering students with the profession is a blind and headlong rush into the pages of a sophomore stoichiometry text, and they do not have a clear overview of the structure and aims of the field until their capstone senior design course. Our hope is that this semi-historical module in the freshman year will help to give students an accurate context for their education at its very beginning, rather than at its end.

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REFERENCES

LOW-COST EXPERIMENTS IN MASS TRANSFER

Part 3. Mass Transfer in a Bubble Column

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S padders are frequently used for dispersing a gas within a liquid when multistage countercurrent contacting is not required. Aeration of fermentation broths and activated sludge, hydrogenation of vegetable oils, chlorination of paper stock, and ore leaching in leachcusa tanks are some important industrial examples of this mode of gas-liquid contacting.

This paper describes a simple experiment that introduces the student to this useful operation as well as to the experimental determination of a mass transfer coefficient and its comparison with values predicted from empirical correlations. The objective of this experiment is the measurement of the mass transfer coefficient for oxygen transfer between a rising gas (air for oxygenation or nitrogen for deoxygenation) bubble dispersion and deionized water in a cylinder.

THEORY

Oxygen is only sparingly soluble in water, and therefore its transfer between gas bubbles and water is controlled by diffusion in the liquid phase. The mechanical motion of rising bubbles creates sufficient agitation that it can be assumed that the liquid phase is well mixed, with a uniform but time-dependent oxygen concentration, $C$. As the gas bubbles rise through the liquid, there is a slight change in their gas composition, but because the contact time in a shallow liquid depth is usually small, the change in the oxygen composition of the gas bubble is small enough to be safely ignored. Also, the oxygen composition in the liquid immediately adjacent to the gas-bubble interface can be considered constant, at $C^*$ (the value for air-saturated water) in the oxygenation case and equal to zero for the deoxygenation case.

The rate of oxygen transfer across the gas-liquid interface may be expressed using a mass transfer coefficient characterizing the liquid-phase resistance to transfer:

For oxygenation

$$N_{O_2} = k_l (C^* - C)$$

For deoxygenation into oxygen-free gas

$$N_{O_2} = k_l (C - 0)$$

$N_{O_2}$ is the molar transfer rate of oxygen on a per-unit area of gas-liquid interface basis. To obtain the transfer rate on a per-unit volume of liquid basis, $N_{O_2}$ must be multiplied by

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two factors, a and $1/(1 - \phi_G)$, where a is the bubble surface area per unit volume of the gas-liquid mixture and $\phi_G$ is the gas holdup (i.e., the volume fraction of the gas-liquid mixture occupied by the gas). Thus, $(1 - \phi_G)$ is the volume fraction of the gas-liquid mixture occupied by the liquid.

$N_{O_2, a}/(1 - \phi_G)$ is the rate of oxygen transfer $(dC/dt)$ into or out of the liquid phase, per unit volume of that phase. Assuming that the liquid phase is well mixed, as is the case in gas sparging, the transfer rate, by conservation of mass argument, must be equal to the rate of change of concentration of oxygen in the liquid phase, Therefore, for oxygen transfer

$$\frac{dC}{dt} = \frac{k_{1a}}{(1 - \phi_G)}(C^* - C)$$  \hspace{1cm} (3)

or, after integration

$$\ln(C^* - C) = \ln(C^* - C_0) - \frac{k_{1a}}{(1 - \phi_G)}t$$  \hspace{1cm} (4)

This equation suggests that a plot of $\ln(C^* - C)$ versus $t$ should yield a straight line.

For de-aeration into an oxygen-free gas such as nitrogen, the appropriate equation is

$$\frac{dC}{dt} = \frac{k_{1a}}{(1 - \phi_G)}t$$  \hspace{1cm} (5)

and for this case, $\ln C$ versus $t$ is the appropriate plot. In Eqs. (4) and (5) above, $C_0$ represents the initial concentration of oxygen in water before starting the aeration (oxygenation) or the de-aeration (deoxygenation) experiment.

The first objective of this experiment is to confirm this simple model by assessing how well the data fit the straight line suggested by the model. A second objective is to evaluate the group of parameters, $k_{1a}/(1 - \phi_G)$, from the slope of the $\ln(C^* - C)$-versus-$t$ or the $\ln C$-versus-$t$ plots.

Once the values of $k_{1a}/(1 - \phi_G)$ are obtained, we can investigate

**If there is a dependence on direction of the oxygen transfer (oxygenation versus deoxygenation), and**

**The influence of the gas flow rate on $k_{1a}/(1 - \phi_G)$**.

A fundamental aspect of engineering science is the ability to predict parameters such as those in the group being measured in this experiment. Treybal[23] provides some details on sparged vessels and appropriate correlations to estimate $\phi_G$, $a$, and $Sh$, or $k_t$. It may be noted that $\phi_G$ can also be determined experimentally from the height of the gas-liquid mixture in a cylinder relative to the water level with no gas flow (which, however, is not convenient at low gas flow rates).

A final objective of this experiment is to compare the experimental values of $k_{1a}/(1 - \phi_G)$ as determined from the slopes of the plots of Eqs. (4) and (5) with the values predicted by the following correlation given by Treybal:

$$Sh_1 = \frac{F_{d} d_p}{cD_j} = 2 + b' Re_{G}^{0.729} Sc_1^{0.546} \left( \frac{d_{p}^{1/3}}{D_j^{2/3}} \right)^{0.116}$$  \hspace{1cm} (6)

where $b'$ is equal to 0.061 for single and 0.0187 for swarms of gas bubbles (other symbols are defined in the nomenclature).

Since the general mass transfer coefficient $F_{1}$ is related to $k_t$ as $F_{1} = k_t S_{BM}$, and noting that for aqueous solutions of sparingly soluble gases, such as oxygen with a solubility of < 9 ppm, the solutions are essentially dilute, $x_{BM} \approx 1$, the above equation may be written in terms of $k_t$ as

$$Sh_1 = \frac{k_{1d} d_p}{D_1} = 2 + b' Re_{G}^{0.729} Sc_1^{0.546} \left( \frac{d_{p}^{1/3}}{D_1^{2/3}} \right)^{0.116}$$  \hspace{1cm} (7)

**APPARATUS**

The apparatus is shown in Figure 1 and is composed of an 8-L acrylic cylinder of 3-inch (0.0762 m) internal diameter, a gas sparger with four 29/1000-inch (0.734 mm) holes, and a Biological Oxygen Demand (BOD) meter (the only instrument that may not be already available in some departments and which may need to be acquired for this experiment). The cylinder is first filled with deionized water, leaving approximately 4.5 inches empty space above the liquid level. The BOD probe is then suspended upside down in the cylinder and connected to the meter. The reason for inverting the probe is to prevent gas bubbles from becoming trapped in the electrodes or coming in direct contact with the cell membrane, both of which result in erratic readings. The top of the cylinder is then covered (Saran® wrap may be used for this purpose) and a few holes are made in the cover for the gas to escape. This cover ensures a nitrogen atmosphere above the water at all times during desorption experiments, thereby preventing the diffusion of air (oxygen) in water during deoxygenation. The gas (air for oxygenation and nitrogen for deoxygenation) is metered through a calibrated rotameter or a gas-flow meter before feeding to the sparger submerged in the cylinder.

**Figure 1. The apparatus.**

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PROCEDURE

The suggested experimental procedure is described below.

1. De-oxygenate the water completely by bubbling nitrogen through the column at a rapid rate. This is evidenced by a nearly zero (ppm) reading on the meter.

2. Begin the first oxygenation experiment by quickly sparging air at the desired flow rate. Start the stop watch at the same time.

3. Take frequent readings of dissolved oxygen concentration with time. Allow the process to continue until water becomes nearly saturated, as evidenced by a constant reading on the BOD meter.

4. Start the deoxygenation investigations by quickly replacing air flow with the nitrogen flow at the same gas flow rate. We found that some time is needed to adjust the nitrogen flow rate to the same value as the air flow rate used during the oxygenation study. Some oxygen desorption therefore occurs during this initial adjustment period and the oxygen concentration in water drops significantly. We therefore recommend that after adjusting the nitrogen flow to the desired value, it may be diverted from the sparger to the fume hood (for safety reasons) and the water re-oxygenated to saturation, and the deoxygenation started by redirecting the nitrogen through the sparger at the previously adjusted desired flow rate.

5. Monitor the change (decrease) in the oxygen concentration of water as was done in step 3 above for oxygenation.

6. Repeat the oxygenation/deoxygenation processes for at least one other gas flow rate.

RESULTS AND DISCUSSION

Oxygenation and deoxygenation investigations were conducted at 8.77 and 82.5 mL/s flow rates of either air or nitrogen, respectively. Plots of $\ln(C^* - C)$ vs. $t$ or $\ln C$ vs. $t$ were prepared. The $C^*$ value obtained from literature was taken as 8.7 ppm ($2.72 \times 10^{-5}$ kmol/m$^3$), and this value was very close to the experimentally observed value at infinite time (the plateau value from the C-versus-t graph).

Figure 2 is a plot of $\ln(C^* - C)$ versus $t$ (Eq. 4) for the oxygenation of water. Data for both air flow rates of 82.5 mL/s and 8.77 mL/s are plotted together for comparison. Both plots are linear and conform to Eq. (4), having a negative slope. The slope for the larger gas flow rate is more negative, as was expected because $k_1 a/(1 - \Phi_G)$ increases with an increase in the Reynolds number.

Figure 3 is a plot of $\ln C$ versus $t$ for the deoxygenation runs at the corresponding nitrogen flow rates of 82.5 mL/s and 8.77 mL/s. These plots are also linear, conforming to Eq. (5) and indicating an increase in $k_1 a/(1 - \Phi_G)$ with an increase in the gas flow rate. It may be noted that one of the curves in Figure 3 shows an apparent leveling-off trend toward the end.
of the experiment. This appears to be due to difficulties in measuring very low oxygen concentrations. In this case, the slope was determined only for the initial portion of the curve.

The experimental values of \( k_1a/(1-\theta_G) \) obtained from the slopes of the plots, and the corresponding \( k_1 \) values calculated from the slopes, are given in Table 1. These values indicate that \( k_1a/(1-\theta_G) \) values for oxygenation and deoxygenation are comparable, suggesting that the direction of mass transfer (from gas to liquid or vice versa) has little effect on the rate of oxygen transfer.

Also included in the Table are the corresponding predicted values of \( k_1a/(1-\theta_G) \) and \( k_1 \) as derived from Eq. (7). The values of \( \theta_G \), \( a \), and \( d_p \) needed for calculating these predicted values were obtained from the methods given by Treybal.\(^2\) As can be seen, the experimental and the predicted values are within \( \pm 12\% \). These results indicate the experiment provides a simple method of comparing experimental results and theoretical predictions.

CONCLUSIONS

Linear plots with negative slopes are obtained for both oxygenation ( \( n[C^−-C] \) versus \( t \) ) and deoxygenation ( \( nC \) versus \( t \) ) operations, conforming to the theory. The values of the slopes of the plots indicate that mass transfer coefficient increases with gas flow rate and is independent of the direction of transfer, i.e., gas to liquid (oxygenation) or vice versa (deoxygenation). There is good agreement between the experimental and the predicted mass transfer coefficient values.

RECOMMENDATIONS

The experimental data presented in this paper are student generated in an undergraduate laboratory course. The procedure is simple and the set of data can be obtained in a usual 3-hour laboratory period. Maintaining the same gas flow rate during oxygenation and deoxygenation provides a challenge during this experiment. Some student groups got better comparison between experimental and theoretical \( k_1 \) values using \( b' \) for single rather than swarms of bubbles. We recommend that the class be subdivided into various groups. Each group may be assigned to study at least two (one low and one high) gas flow rates, with each group given a different set of flow rates than the other groups. The groups can also study the dependence of mass transfer coefficient on the effects of 1) varying the liquid viscosity by adding sucrose to the water, 2) the orifice diameter, or 3) the number of holes in the sparger. Each group should compare experimental and predicted values of \( k_1a/(1-\theta_G) \).

ACKNOWLEDGMENTS

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NOMENCLATURE

- \( a \): specific surface area, \( m^2/m^3 \)
- \( b' \): constant, dimensionless
- \( c \): total liquid concentration, \( kmol/m^3 \)
- \( C \): oxygen concentration in water at any time, \( kmol/m^3 \)
- \( C^0 \): oxygen concentration in water saturated with air, \( kmol/m^3 \)
- \( \phi_G \): initial oxygen concentration in water, \( kmol/m^3 \)
- \( d_p \): average bubble diameter, \( m \)
- \( D \): diffusivity of oxygen in water, \( m^2/s \)
- \( F \): general mass transfer coefficient, \( kmol/m^2/s \)
- \( g \): acceleration due to gravity, \( m/s^2 \)
- \( k \): liquid side mass transfer coefficient, \( m/s \)
- \( N_{O_2} \): oxygen flux, \( kmol/m^3/s \)
- \( \Re_G \): gas Reynolds number based on slip velocity ( \( d_pV_1/\rho_l \) ), dimensionless
- \( \Sc \): Schmidt number based on liquid properties ( \( \mu_1/\rho_1D_1 \) ), dimensionless
- \( \Sh \): Sherwood number based on gas-bubble diameter ( \( F_1d_p/cD_1 = k_1d_p/D_1 \) ), dimensionless
- \( V_G \): superficial gas velocity, \( m/s \)
- \( V_1 \): liquid velocity, \( m/s \)
- \( V_s \): slip velocity, i.e., relative velocity of gas and liquid, \( = V_G/\phi_G - V_1/(1-\phi_G) \), \( m/s \)
- \( \ln \): logarithmic mean mole fraction of non-diffusing components

GREEK SYMBOLS

- \( \mu_1 \): liquid viscosity, \( kg/ms \)
- \( \rho_1 \): liquid density, \( kg/m^3 \)
- \( \phi_G \): gas hold up, dimensionless

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A SIMPLE EXPERIMENT FOR
MASS TRANSFER

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Some papers related to chemical engineering education that have been published\(^1,2\) are different from the standard laboratory experiments we find in chemical engineering. These new experiments, called unstructured research experiments, are simple, inexpensive and capable of yielding meaningful results. We would like to introduce a simple experiment in this paper that requires very simple equipment and which illustrates one of the basic problems of mass transfer—more specifically, a technique that calculates the interphase mass transfer coefficient using phase change material from laboratory data.

This paper describes an experiment where students take the laboratory data and calculate the interphase mass transfer coefficient for a fluid passed over a sphere, obtaining correlations for solid-gas mass transfer. Then they can compare these results with the correlation described in the literature or they can develop a realistic mathematical model to describe the sublimation process.

We present the experiment by saying that we want them to find the mass transfer coefficient for a sublimation process. The students must choose a phase change material and determine the influence of the various experimental parameters (such as gas velocity, gas temperature, initial particle mass, etc.) on the mass transfer coefficient and calculate its value for a given experiment. We tell them that there is no experimental setup for this purpose, but that the laboratory has a hair dryer, a thermometer, a scale, and an infrared thermometer available.

After the problem is presented to the students, they have to study the literature to become familiar with the process of phase change. Finally, they must develop a mathematical model that describes the sublimation process.

EQUIPMENT AND EXPERIMENTAL PROCEDURES

A schematic diagram of the experimental apparatus is shown in Figure 1. The components are a hair dryer, a tube, a thermometer, a scale, a Pitot tube, and an infrared thermometer. The experimental procedure consists of introducing a naphthalene ball into the tube. This ball is held to the wall by a copper wire. The air leaving the hair dryer passes through the electrical resistance where it is heated, then goes around the naphthalene ball and the sublimation process begins.

The variation of the weight of the naphthalene ball versus time permits calculation of the interphase mass transfer coefficient of the experiment. The experiment is so simple that we only need to measure the weight variation of the ball for different flows of air and temperatures; this can be done with a scale and a stopwatch.

THEORETICAL

The rate of mass transfer between a solid and the flow of air is usually described by
\[ \dot{m} = K_{sg} A \left( C_s - C_g \right) \]  

(1)

where

- \( \dot{m} \) sublimation rate
- \( K_{sg} \) solid-gas mass transfer coefficient
- \( A \) external surface of the particle
- \( C_s \) concentration on the particle surface
- \( C_g \) concentration inside the approaching air

In practice, \( C_s = 0 \) because the approaching air is free of diffusing components. Then, Eq. (1) can be written as

\[ \dot{m} = K_{sg} A C_g \]  

(2)

or

\[ \dot{m} = K_{sg} \frac{p_s M}{RT_s} \]  

(3)

where

- \( R \) gas law constant
- \( M \) molecular weight of the sublimated substance
- \( T_s \) temperature on the surface of the particle
- \( p_s \) vapor pressure of the pure substance at saturation

In the case of the naphthalene ball, the vapor pressure of the pure substance at saturation (Eq. 3) is given as

\[ \log_{10}(p_s) = 13.575 - \frac{3728.75}{T_s} \]  

(4)

with \( p_s \) in N/m² and \( T_s \) in K.

A mass balance on the sublimated solid is

\[ \frac{dW}{dt} = -\dot{m} = -K_{sg} A \frac{p_s M}{RT_s} \]  

(5)

where \( W \) is the total mass of substance remaining in the solid phase at any time \( t \),

\[ W = \frac{4}{3} \pi r^3 \rho_s \]  

(6)

with \( \rho_s \) being the density of the solid particle.

The corresponding interfacial area is

\[ A = 4 \pi r^2 \]  

(7)

From Eqs. (6) and (7), we obtained

\[ A = \left( \frac{36 \pi W^2}{\rho_s^3} \right)^{1/3} \]  

(8)

Substituting in Eq. (5), we get

\[ \frac{dW}{dt} = -\frac{\dot{m}}{\rho_s} = -K_{sg} \left( \frac{36 \pi W^2}{\rho_s^3} \right)^{1/3} \frac{p_s M}{RT_s} \]  

(9)

This equation can be integrated to yield the following relation between time and the fraction of solid remaining in the solid phase:

\[ \left( \frac{W}{W_0} \right)^{1/3} = 1 - K_{sg} \left( \frac{4 \pi}{3 W_0 \rho_s^2} \right)^{1/3} \frac{p_s M}{RT_s} \]  

(10)

The plot of the variation of the fraction of solid remaining in the ball versus time will produce a straight line. Calculating the slope of this line, the student will obtain the interphase mass transfer coefficient.

**RESULTS AND DISCUSSION**

Figure 2 shows the variation of the weight of the naphthalene ball as a function of time for two different experiments. This graph illustrates the importance of the temperature for the experiment because the flow rate of air was kept constant during the entire experiment. If we increase the temperature of the experiment, the fraction of solid remaining in the naphthalene ball decreases and the interphase mass transfer coefficient increases.

Figure 2 shows that we have a linear
relationship between the variation of the solid remaining in the ball and the operating time. The slope of this line allows calculation of the interphase mass transfer coefficient using Eq. (10).

In Figure 3 we can see the variation of the mass transfer coefficient with the initial particle mass of the naphthalene ball if we maintain the gas temperature and gas velocity constant ($T_o = 62.5^\circ C$, $u_o = 3\, m/s$). It is obvious that when the particle mass increases, the mass transfer coefficient decreases.

During the process of phase change, the particle size changes and the mass transfer coefficient might also change. In order to check this, the experiment must be performed to determine if a single value of the mass transfer coefficient describes the entire course of an experiment.[2]

In Figure 4 we have presented the model predictions with a constant value of the mass transfer coefficient that describes the experimental data obtained in an accurate way. The experiment can be too large if the flow and air temperature are too low, however. Therefore, when determining a mass transfer coefficient for a given time, it can be considered that a single data point was taken and it was assumed that the calculated mass transfer coefficient was representative of the whole experiment.

After performing the experiment, the students have to discuss a number of points in the analysis and conduct further discussion of their results. For example

- Have they determined if the particle size is important to calculate the interphase mass transfer coefficient?
- Have they determined if a simple value of the interphase mass transfer coefficient describes the entire course of an experiment?
- Were they able to find a literature correlation for $K_{0s}$?
- Did they check to see if the air temperature did not change significantly during the experiment?
- If they found initial data scatter, did they try to explain why that was so?
- To determine the solid mean temperature, we used an infrared thermometer; if we didn’t have this equipment in the laboratory, how would the students mea-

We have found that the study of the naphthalene ball adds interest to the mass transfer experiment. The technique is safe, inexpensive, rapid, and capable of yielding meaningful results.

![Figure 3. Variation of the mass transfer coefficient with the initial particle mass.](image)

![Figure 4. Comparison of the model prediction and experimental data.](image)
Outcomes Assessment Methods

Continued from page 131.

fer the well-defined requirements of the Engineering Top­

ics Criteria when struggling to implement an outcomes

For chemical engineers, it is likely that determining cur­
riculum goals will not be the most significant obstacle, es­
pecially since EC 2000 provides a suggested list of program
goals.[3] The outcomes assessment measures described above
are examples that have been used successfully, but they are
by no means exhaustive. The two lessons learned from these
outcomes assessment measures are 1) that multiple mea­
ures are essential, and 2) that we must look at what is
already being done to identify potential outcomes measures.
Probably the most difficult part of an assessment plan to
implement is the feedback. Faculty unaccustomed to dis­
cussing curricular issues and individual student outcomes, or
to receiving feedback will have to change their attitudes.

CONCLUSIONS

Outcomes assessment is a reality looming on the hori­
zon. Within the next five years or so, all chemical engi­
neering programs will have a functioning assessment plan.
The methods described in this paper present a framework
for developing an assessment plan. The goal is to de­
velop a plan that benefits everyone involved. The result
is a win-win-win situation in which students learn more,
faculty become better teachers, and employers are more

satisfied with their employees.

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HIGHER-ORDER THINKING IN THE UNIT OPERATIONS LABORATORY

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Most faculty members are aware that too many engineering courses emphasize "plugging and cranking" on well-defined, close-ended, numerical problems at the expense of helping students become better critical thinkers and engineering practitioners. As a result, and in sharp contrast to other professions such as medicine and law, too few of our engineering graduates are capable of immediately practicing engineering when they leave college. Yet, industry expects to hire engineering graduates who can "go beyond the numbers" by understanding how technical results fit into a larger systems perspective, who can integrate knowledge to find new solutions to problems rather than relying on a traditional reductionist approach, and who can communicate the results of their work to many different audiences. In short, they want engineers who can "think outside the box."

In response to these expectations, many of the new ABET Engineering Criteria 2000 features focus on professional practice, including "an ability to design and conduct experiments as well as to analyze and interpret data; an ability to identify, formulate, and solve engineering problems, an ability to function on multi-disciplinary teams; and an ability to communicate effectively." We believe that the unit operations laboratory provides an ideal setting to help chemical engineering students become better engineering practitioners. At the Colorado School of Mines (CSM), we offer the unit operations laboratory as an intensive six-week summer experience designed to enhance students’ higher-order thinking skills and familiarity with many aspects of chemical engineering professional practice, including data collection and analysis, evaluation and interpretation of results to draw meaningful conclusions, and effective communication to a variety of audiences.

As presently taught, the course relies heavily on a constructionist approach—that is, the cognitive theory suggesting that learners construct their own internal interpretation of objective knowledge based, in part, on formal instruction, but also influenced by social and contextual aspects of the learning environment and previous life experiences. This view suggests that students “make their own meaning” of what they are learning by relying on mental models of the world, models that may be correct or may contain strongly held misconceptions. Rather than acting as acknowledged authorities transmitting objective knowledge to passive students, laboratory faculty use coaching and Socratic questioning techniques to help students understand complex technical phenomena by constructing mental models that reflect reality as perceived by acknowledged experts while minimizing models containing significant misconceptions.

In addition to experimental work, extensive use of statistics to analyze and evaluate data and instruction and practice in technical oral and written communication are also important facets of the course. In this paper, we present details of
the course organization, methods we use to promote higher-order thinking, expected student outcomes, and examples illustrating how students’ higher-order thinking and communication abilities develop during the course.

COURSE DESCRIPTION

All CSM chemical engineering students (approximately 90-100 per year) are required to complete a rigorous six-credit-hour summer field session following their junior year in which they spend six weeks conducting, analyzing, and reporting the results of a series of sophisticated unit operations experiments. Expected student outcomes during the course include:

- Reinforcing understanding of basic concepts in momentum, heat, and mass transport, and statistics
- Learning how to analyze, synthesize, and evaluate experimental results
- Improving technical oral, written, and graphic communication skills
- Enhancing team-building and leadership skills

To facilitate development of each student’s engineering abilities, supervising faculty place as much responsibility for the planning, execution, analysis, evaluation, and reporting of experiments on the students as possible. Each student performs eight of the ten experiments listed in Table 1, working in teams of two or three. Teams are randomly sorted from experiment to experiment so that students work with all their peers in the course and each student has the opportunity to serve as a “team leader” on several experiments. Since the students have received extensive team-building instruction and practice in the CSM EPICS (Engineering Practices Introductory Course Sequence) program,[3] no additional team-building work is required in the laboratory. As a capstone project, student teams also design a new unit operations experiment or retrofit an existing piece of equipment.

Each experiment consists of the five steps shown below; student teams must satisfactorily complete each step to receive credit for the experiment:

- “Prelab” preparation
- “Prelab” oral presentation to supervising faculty member
- Operation of the equipment to collect data
- Analysis, synthesis, and evaluation of data including statistical error analysis
- Presentation of results orally or in writing, including preparation and review of draft written reports

Preparing and Presenting the “Prelab”

The afternoon prior to performing an experiment, each student team meets to become familiar with the general experimental objectives and safety guidelines provided by faculty supervisors (an example set of objectives is shown in Table 2), to study the equipment and how to measure and model its performance, to create a list of detailed experimental objectives, to develop an experimental design for data collection, and to decide what statistical analysis strategies will be used with the experimental data.

We do not provide detailed step-by-step instructions on how to conduct or analyze an experiment—less than one page of written guidelines (including safety issues) are typically available for each experiment. Instead, students are expected to educate themselves on the appropriate background knowledge required to meet each experiment’s objectives, using their textbooks and other information sources; faculty supervisors act as coaches or mentors to the teams, but do not portray themselves as authority figures. Faculty rarely answer questions directly, but instead help students find their own answers using prompts such as “How do you know that?”, “How would you estimate or measure X?”, “Have you considered Y?”, “What are the limitations of that correlation?”, or “How good is that assumption?”

Early on the morning the experiment is scheduled, each

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student team presents the results of the “prelab” preparation to a supervising faculty member who questions members of the team on all aspects of the experiment, including background theory, working equations, data collection, measurement errors and data reproducibility, and data analysis and evaluation. At the beginning of the course, students need more direct feedback to help them establish realistic objectives and correctly compute results from experimental data. As the students become more adept at routine data collection and analysis, faculty begin to ask more complex questions to begin the process of nudging students to think in new and more sophisticated ways.

We believe the “prelab” exercise is a crucial part of each experiment because students acquire a good understanding of the experiment and our expectations before beginning data collection. Depending on the degree of preparation and understanding, each team may spend from 15 minutes to 2 hours in this examination; no team is allowed to begin work in the laboratory until the examination has been passed. Our objective here is to ensure that students have thoroughly developed their experimental objectives and their data collection and analysis strategy; the laboratory itself is not the place to begin this process.

**Working in the Laboratory** • Once they are in the laboratory, each student team controls its own destiny and operates without input from faculty supervisors or teaching assistants (except for potential safety issues). Students make decisions about ranges of data to collect, about the amount of data to collect, and about conducting reproducibility runs. Depending on the complexity of each experiment, they may remain in the laboratory for anywhere from four to eight hours collecting data. They often use laptop computers for “real-time” data analysis, and several of the experiments are computerized for automatic data logging directly into personal computers.

**Working with the Data** • With data in hand, the team begins the process of data analysis, comparison of results with theoretical predictions or accepted correlations, and statistical error analysis. This is an intense time for the team members—they must either prepare and deliver a 20-minute oral presentation describing their work one day after completing the experiment or must submit a draft written report five days after completing the experiment. In either case, they must complete calculations, develop appropriate correlations of engineering parameters such as friction factors or heat-transfer coefficients, prepare figures and tables of results, develop error propagation and statistical analyses, provide logical explanations for any deviations of their results from expected values, and develop overall conclusions based on evaluation of their work.

We have three reasons for requiring short turnaround times for oral and written reports. First, the laboratory schedule requires students to move quickly from experiment to experiment in order to complete eight experiments within the six-week course. Second, time demands absolutely require effective teamwork—no individual student alone can possibly complete all the tasks of an experiment. Third, and perhaps most important, we want to encourage students to plan and study the experiment thoroughly during their “prelab” preparation. This allows them to develop their higher-order thinking skills by concentrating on developing meaningful conclusions from their results rather than just reporting routine lists of numerical data.

**Communicating the Results** • Students produce four oral and four written reports on experiments completed during the course. In addition, both an oral and written report are required as part of the final design project. Oral presentations are attended by other students in the course and by one or more faculty supervisors; presenters are expected to focus largely on the conclusions drawn from their results and reasons for any obvious discrepancies from expected trends. Once again, faculty use Socratic questioning to probe for evidence of analysis, synthesis, and evaluation by student teams. Each written report is submitted first in draft form for review by the faculty supervisor and a technical communication specialist. Draft review meetings are then held with individual student teams to provide feedback and to discuss remaining difficulties in technical and rhetorical content before the final version of the report is submitted for grading.

**Other Course Activities** • To further help students improve their thinking and writing skills, during the first few weeks of the course we conduct a series of workshops that focus on statistics and data analysis, experimental design, and written communication. For example, as part of the experimental design workshop, we ask students...
to brainstorm and share ideas for extending the analysis of
the experiment they are currently conducting beyond the
objectives stated in their “prelab.” This exercise works
well to help students think and work beyond the obvious
outcomes for each experiment and encourages stu-
dents to “think beyond the box” in the course.

The course culminates in a
week-long capstone project in
which student teams are asked
to design a new laboratory ex-
periment or to retrofit an ex-
isting piece of equipment to
improve its performance. The
design project allows students
to apply the knowledge and
skills learned in the laboratory
experiments in a new engi-
neering context. In recent
years, students have designed
experimental systems to study gas/liquid flow in horizon-
tal and vertical pipes, gas/solid fluidization, reverse os-
mosis, air separation using membranes, and transient dry-
ing of wet granular solids.

DEVELOPING, MONITORING, AND
ASSESSING HIGHER-ORDER THINKING
AND COMMUNICATION SKILLS

As we designed the unit operations laboratory course to
help students develop their higher-order thinking and com-
munication skills, we were guided by Benjamin Bloom’s
taxonomy of cognitive objectives;[6] the taxonomy is also
useful as a performance assessment framework to determine
whether students achieve the expected outcomes listed ear-
lier. Students are assessed by course faculty (in each “prelab”
session, oral presentation, and written report) on their ability
to demonstrate a thorough understanding of basic transport
phenomena and unit operations concepts and their use of
statistics to analyze and evaluate experimental data. Stu-
dents’ communication and team skills are also assessed by
the faculty within the context of laboratory work. In addi-
tion, each student evaluates the contribution of each team-
mate after each experiment is completed. In this way, stu-
dents are individually held accountable for their contribu-
tions to the team’s success or failure. Students who receive a
poor peer evaluation are immediately counseled by course
faculty—repeated low evaluations result in an overall grade
reduction or withdrawal from the course.

As shown in Table 3, Bloom’s model proposes six classes
of cognitive behavior, ranging from simple recall of facts or
ideas (knowledge) through explanation of relationships and
data inference (analysis) to sophisticated value judgments

<table>
<thead>
<tr>
<th>TABLE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bloom’s Taxonomy of Cognitive Behavior</strong>[6]</td>
</tr>
<tr>
<td><strong>Evaluation</strong></td>
</tr>
<tr>
<td><strong>Synthesis</strong></td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
</tr>
<tr>
<td><strong>Application</strong></td>
</tr>
<tr>
<td><strong>Comprehension</strong></td>
</tr>
<tr>
<td><strong>Knowledge</strong></td>
</tr>
</tbody>
</table>

about the quality or merit of an idea using data (evaluation).
The term “higher-order thinking” usually refers to the higher
three levels of cognitive behavior in the taxonomy—analy-
sis, synthesis, and evaluation.

In this section, we present excerpts from laboratory re-
ports to illustrate how students’ thinking develops during the
six-week session. The process is developmental, slow, and at
times frustrating and painful for some students. But we have
found that all students in the course, regardless of academic
preparation and background, can improve their ability to
think and communicate if given appropriate feedback and
encouragement by faculty supervisors and peers.

**Lower-Level Thinking**

During the first two weeks of the course, students tend to
function in modes of thinking that have been reinforced in
earlier courses—simply reporting facts and straightforward
numerical results from the experiment. We predominately
see laboratory reports containing statements such as

- Our results show that the orifice coefficient is 0.55. In
  industry, the accepted coefficient is 0.61. Therefore, our
  results don’t agree with the correct value.

- The experimental acoustic velocity was found to be 1444.0 ft/
  sec, which is 27.2% different from the theoretical value.

- Our heat-transfer coefficients ranged from 365 to 704 Btu/hr
  ft² °F, which are well within the accepted range of 200-1000
  Btu/hr ft² °F.

- We compared our heat transfer correlation to the accepted
  correlation. We found that our exponent on the Reynolds
  number was lower, but the coefficient was greater. The
  exponent on the Prandtl number was about the same.

At this point, students believe that reporting results, per-
haps with a simple numerical comparison to an accepted
value or range of values, constitutes data analysis. Although
they don’t realize it, the message at this point is “Here’s
what we got; you (the reader) figure out what it means.”
Early in the course, students don’t yet have the ability to
critically analyze their data, to use error and statistical analy-
sis, and to derive meaningful conclusions because they have
never been taught how to do it nor were they expected to do
it. Previous laboratory and lecture courses reinforced the
idea of one correct answer for every problem and the mis-
conception that the teacher is the only authority figure in
possession of all knowledge. When students are confronted
with “incorrect” results (i.e., results that don’t agree exactly
with theory or accepted correlations), even though the ex-
periment was done “correctly,” they become puzzled and often respond with illogical and sweeping conclusions such as “all our data are bogus” or “the experimental apparatus is obviously broken.”

**The Beginning of Analysis** • By about the third week (after completing two oral and two written reports), most students begin to understand how to analyze their data. At this point, we see report excerpts such as

- Our friction factors ranged from 0.0073 to 0.091 with a mean error from accepted values of 32%. Error propagation estimated experimental errors at 31%. The biggest contribution to the error came from pressure-drop measurements. Finally, we conclude that all of our experimental friction factor values were below values from the Moody diagram.

- Our measured values of heat-transfer coefficients ranged from 571 to 1079 Btu/hr ft °F and differed from accepted correlation values by 2.6% to 36%. All percent differences were within the estimated error propagation; as a result, we conclude that our measurements are as precise as the instrumentation allows and contain no experimental bias.

- Orifice coefficients using velocities measured with the anemometer varied from literature values of 19-66%, while coefficients using Pitot-tube data varied by 8-54%. This difference was attributed to human error in using the anemometer and reading Pitot-tube fluctuations.

Now students have progressed beyond routine data reporting to include a more detailed comparison with accepted results, which indicates the beginning of legitimate data analysis and the search for trends and correlations among experimental variables. The students’ message has become, “Here’s what we got, and here’s how it compares quantitatively to accepted results.” Often, however, inferences that could be drawn from quantitative comparisons of experimental and literature results are implied but not yet explicitly stated. Students at this stage are still reluctant to state definitive conclusions about the data. Instead, we see general statements such as “We conclude our data are unbiased” or “Our results indicate the presence of human error.” Ironically, writing quality tends to deteriorate as students are pushed to more sophisticated levels of data analysis and evaluation. Since writing and thinking are so closely connected, students who are in the process of developing new modes of thinking often have significant trouble articulating their ideas.

**Moving from Analysis to Evaluation** • By the fifth week, students are quite adept at reporting routine results and most are capable of some reasonable data analysis. They are also capable of synthesizing knowledge from different subject areas (e.g., fluid mechanics, heat and mass transfer, statistics) without major difficulty. But developing the ability to evaluate their results critically and to draw definitive conclusions from their work is very difficult for the students, and supervising faculty spend most of their time coaching the teams to help them meet this goal. At this point, the better students begin to write reports containing excerpts such as

- For the 0.1-inch diameter orifice plate, we found an orifice coefficient of 0.65 with a 95% confidence interval of 0.60 to 0.70, which compares favorably with the accepted value of 0.61. Thus, we conclude that the orifice meter is working properly and operating as expected.

- As shown in Table X, the agreement between the measured velocity of sound using conservation of mass and the orifice meter equation varied by less than 7%, indicating consistent experimental orifice meter data. Experimental acoustic velocity results are a function of orifice diameter. This result shows an error in the estimation of the pressure ratio at choking because the acoustic velocity should be independent of orifice diameter.

- The experimental friction factor values from the steel tubing tended to lie above the correlated smooth pipe curve, indicating the tubing had an inside roughness greater than

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**TABLE 4**

**Summary of Student Feedback Results**

<table>
<thead>
<tr>
<th>Question</th>
<th>Percentage Disagreeing or Strongly Disagreeing</th>
<th>Percentage Neutral</th>
<th>Percentage Agreeing or Strongly Agreeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>I better understand the differences between lower-order thinking and higher-order thinking.</td>
<td>0.0</td>
<td>12.2</td>
<td>87.8</td>
</tr>
<tr>
<td>My higher-order thinking skills have improved.</td>
<td>2.4</td>
<td>7.3</td>
<td>90.3</td>
</tr>
<tr>
<td>My knowledge of statistics and error analysis has improved.</td>
<td>2.4</td>
<td>4.9</td>
<td>92.7</td>
</tr>
<tr>
<td>My written communication skills have improved.</td>
<td>2.0</td>
<td>6.8</td>
<td>91.2</td>
</tr>
<tr>
<td>My oral communication skills have improved.</td>
<td>5.9</td>
<td>5.6</td>
<td>88.5</td>
</tr>
<tr>
<td>My ability to work in teams has improved.</td>
<td>7.3</td>
<td>22.0</td>
<td>70.7</td>
</tr>
<tr>
<td>I believe this course was worth the time and effort.</td>
<td>7.2</td>
<td>9.8</td>
<td>83.0</td>
</tr>
</tbody>
</table>

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Chemical Engineering Education
expressing their newly developed ways of thinking.

We calculated the roughness of the steel tubing to be 0.00053, which is 15% higher than the literature value for steel pipe in [our text]. We conclude the tubing has a rough deposit on the inside wall, maybe from hard water.

Students have now moved beyond data reporting and simple comparisons and have begun developing *inferences* about what the results actually mean. Their message has become, “Here’s what we got, here’s how it compares to accepted results, and therefore, here’s what we think it means.” Because most of the students lack extensive industrial experience, the inferences are generally not very sophisticated, but they do help students begin to understand the limitations of published results and correlations and the importance of engineering judgment in professional practice. We also observe that by the fifth week, the quality and depth of writing begins to improve—students are becoming more capable of expressing their newly developed ways of thinking.

**STUDENT FEEDBACK ON THE COURSE**

At the end of each six-week session, we ask students to provide feedback about what they believe they learned in the course; a summary of results from the first session of 1997 are shown in Table 4. Approximately 90% of the students believed they better understood the concept of higher-order thinking and that their own higher-order thinking skills improved in the course; about the same percentage also believed their oral and written communication skills had improved, while nearly 93% believed their knowledge of statistical analysis improved.

Overall, 83% of the students believed the course was worth the tremendous time and effort involved (approximately 60-80 hours per week). One student commented that “for all the pain and suffering, field session was definitely worth it. I learned more in six weeks than during three years of class.” Another stated that “field session was very difficult, but it was also rewarding. I think its focus should continue to stress what will be expected of us on the job.”

We receive similar feedback from our alumni, a majority of whom list the unit operations laboratory as the most valuable course they took at CSM.

**CONCLUSIONS AND RECOMMENDATIONS**

The unit operations laboratory course we have described is designed to provide undergraduate chemical engineering students with instruction and practice in developing their higher-order thinking and communication skills. Faculty help students improve these skills throughout the course by acting as coaches and Socratic questioners rather than lecturers. Students are generally not able to effectively analyze and evaluate experimental data when they begin the course, but do improve during the six-week laboratory session. The net result is students who have acquired a deeper and more meaningful understanding of chemical engineering fundamentals and professional practice.

For those faculty who would like to use the unit operations laboratory to promote enhanced higher-order thinking in their students, we offer the following observations and recommendations:

- Although the “total immersion” summer session is advantageous for helping our students improve their higher-order thinking and communication skills, our techniques should also work using a conventional laboratory course schedule offered during the academic year.
- We know of no techniques that magically help students become better thinkers and communicators—the keys are to set high expectations at the outset of the course and to provide a laboratory setting that facilitates student growth and development by maximizing faculty/student interaction. The “prelab” conference is a crucial part of the course structure because it allows faculty to nudge students toward higher levels of thinking and problem solving in each experiment.
- Expect that the development of higher-order thinking skills will be a slow and sometimes frustrating process for most students. Be aware of where each student is comfortably functioning on Bloom’s taxonomy and push him or her to the next level. Think of the process as building a scaffold one level at a time—each level must be reached and solidified before attempting to move on to higher levels.
- Depending on the background and experience of students in the course, instruction and practice in team-building skills may be necessary. Don’t group students together and expect they will automatically form a functioning team unless they have had previous practice in doing so.

**REFERENCES**

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 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.

THE EXPERIENCE FACTOR
Internships Through the Eyes of Students and Industry

Typically, the voice heard in these contributions is the faculty or industrial mentor who supervised the internship. While the mentor is present in this article, the dominant voice is that of the student who experienced several internships and has reflected on the value of his experiences and what he has learned from them. Therefore, although this “Learning in Industry” contribution is somewhat different than the typical article in this series, I think you will find it useful and interesting.

Bill Koros, Editor

Clearly, there are many motivations for industry to involve students in programs as side-by-side workers with degree-holding engineers. This article describes a special example of such a program, titled INROADS, aimed at injecting bright minority students into the professional world of engineering. The tone of the article differs a bit from other “learning in Industry” contributions, but its emphasis on the student perspective of such programs should be useful to those more interested in “outcomes” rather than in formal requirements as a measure of education. One outcome of a successful intern experience is the establishment of a link between the student and his or her mentor that extends well beyond the period of the formal internship.

A short industrial perspective is offered first, followed by a description of the formal INROADS program. Finally, there is a personal commentary of how the industrial commitment and private efforts like INROADS impacts a minority student seeking to explore the industrial world of engineering as a career option.

An Industrial Perspective of Internships
by Bill Campbell, Apache Corporation

Summer internships are extremely valuable, both to the student and to the recipient company. In experiencing the daily operation of industry prior to leaving the classroom, the intern can avoid some of the many “rude awakenings” that lurk outside of the college environment. For example, there are fewer days to sleep late or to take off, there are work assignments that have significant monetary impact on the company, and there are numerous opportunities for social interaction. Some other benefits to the student are:

- The internship provides the invaluable experience of “teamwork.” Regardless of one’s intelligence, GPA, or work ethic, working with other professionals in a team environment is a fact of life in today’s corporate America. Functioning as an integral part of a team is
critical in the business world and is a highly regarded skill that can be gained through work experience.

- The internship gives the student a chance to answer some “gut-level” questions, such as: Do I like working in this industry? Would I enjoy working for this company? Am I more suited for office or field work? What position would I like to attain in the future?

- The internship gives the student confidence to compete in today’s business world. The intern soon realizes that he or she not only can meet the demands of corporate America, but can also exceed them. This kind of success allows the individual to raise his or her own self-esteem in order to pursue a particular study and chosen career.

The company benefits from internships by having someone who can go forward with projects that have been put on the “back burner.” Most companies in the 90s have some low-priority projects that need to be attended to but which cannot be immediately completed due to current staffing levels. Another benefit is that interns can provide additional technical support through computer applications that are taught in today’s classrooms but which are not readily available to the seasoned professional. The intern also provides a preview of his or her work habits prior to the company extending an offer of permanent employment. Additional considerations of internship are that the student often gives the professional a new perspective in regard to completing job assignments and enlightens the professional as to what is being taught in today’s classroom.

In summary, the relationship between the intern and the company can be described in 90s terminology as a “win-win” situation. That is, both parties benefit from the arrangement.

The INROADS Program • The internship experience described here resulted from a program that is now over 25 years old, titled INROADS, which provides a unique vehicle for students from under-represented groups to enter the business world.

Specifically, INROADS is a private, nonprofit organization with the mission “to develop and place talented minority youth in business and industry and prepare them for corporate and community leadership.” Frank C. Carr founded the program in 1971 in Chicago. What began with just a handful of high-school students from the Chicago barrios has now expanded to fifty affiliates across the United States, Canada, and Mexico. Currently, there are 6,000 interns, 913 sponsoring companies, and 6,500 graduates of the INROADS program from Hispanic, African, and Native American backgrounds.

The program involves more than just an internship to occupy the student’s time during the summer break. The interns benefit from tutoring and academic support, from training workshops in seven skill areas (communication, self-management, business sophistication, management, valuing diversity, academic/technical, and community involvement and leadership), from coaching on career goals, and from networking with ambitious students and professionals who have similar goals. In the performance evaluation, the interns and their business coordinators meet at the end of the summer tour to review and provide feedback on the intern’s performance.

Student Perspective of Internships
by Damian Gumpel

Having just graduated from high school and with college looming on the horizon, I wasn’t sure I had made the right choice in accepting a summer internship. At that point in my life, I wondered if the best thing to do with my summer might be to put the word “school” in my brain’s archives and just rest, or maybe get a job that required no thought. Fortunately, I had already made the commitment, and I felt I had to keep it. So thoughts of packing my bags with sandals and sunscreen and heading off to “Bumville” for the next three months died on the vine. The resulting intern experience was not only valuable but also came at a key time in my life. My first summer internships were at Apache Corporation as part of the INROADS program, and my most recent internship was with 3M Corporation, which I believe I received as a result of my previous intern work experience.

General Benefits of the Internships • Beside the obvious fact that an internship is a summer job that brings much-needed income to the coffers of a college student, it provides a plethora of intangible benefits and opportunities. As is true with just about everything else in life, however, what you get out of an internship is in direct proportion to what you put into it. Some of the skills that an internship can provide to a willing individual are:

Organization. For the first time in my life, someone besides my parents was looking over my shoulder on a daily basis. As the number of tasks and their complexity increased, it became obvious that I had to develop a sense of organization and an awareness of my work area since I was the one responsible for knowing where everything was. I found I was more inclined to contribute ideas when everything was neat and tidy. By forcing myself to become organized, I developed a certain discipline that spread out and affected other areas of my work ethic. This skill was put to good use more than once in my journey through the demanding chemical engineering curriculum.

Communication. Society clearly could not have evolved to its current complexity without efficient communication at various levels of subtlety and through various media. The same fact applies to work,
where an ineffective communicator often does not advance through the ranks due to that deficiency alone. The ability to communicate involves more than just having a decent vocabulary; it is what you say and how you say it that can spell success or doom. There is a certain sense of professionalism that is prevalent within the confines of an office environment. Granted, the extent of this professionalism can vary greatly depending on the location and the prevailing culture, but it is up to the individual to know when and how to communicate in the most productive fashion. I have found that if I approach two different people for assistance in a manner that is unique to each individual, both instances will usually produce a positive result. But switching my approaches would result in a couple of blank stares.

This idea also applies to written communication, where the two most important rules are: keep it brief and get to the point. Gone are the college days of rambling essays (a definite blessing for most of us). I have noticed, however, that it is often harder to compress my thoughts than it is to expand upon them. For example, when I was first asked to draft memos to my boss, my mentor would find and mark superfluous material and return them to me time after time. I sometimes felt as if I could do nothing right, and it was tough for me to change, which leads me to the last skill, humbleness.

- Humbleness. The smartest, most talented students entering the business world can immediately look like sardines amid the sharks. More often than not, they find themselves surrounded by people who are at least half again as old as they are, who have considerably more practical experience, not to mention plain old life experience, and who most often hold a more advanced degree than the student. While some coworkers will try to put the student “in his/her place,” most will extend a hand of friendship and assistance. As long as the intern doesn’t acquire a reputation of being cocky, closed-minded, or brash, he or she is on the right track.

**Apache Corporation Experience**

- Although my summer work at Apache corporation was not in the “traditional” chemical engineering fields, it was extremely beneficial in preparing me for industrial work in general. During my four years of summer internships at Apache Corporation, I worked on a wide range of assignments, ranging from trivial to important. On reflection, I realize that many of these tasks were significant. Listed below are some of my most important assignments, with a brief description of how my chemical engineering education was put to use in executing them.

- **Field Studies on Marginal Oil and Gas Properties.** This work is generally considered low priority for the professional, but it needs to be completed prior to the sale of any property in order to identify its value and to evaluate any remaining potential. Using my knowledge of unit operations, it gave me the opportunity to calculate such things as fluid flow, permeability, pressure loss, and static head.

- **Reserve Bookings on New Field Discoveries.** This involved applying the different terms and formulas used in an economic analysis (NPV, IRR, and discount rate) that I acquired from a chemical engineering elective on economic analysis and applications.

- **Preparing Material for Presentation to Management at the Quarterly Reviews.** This work is significant since these sessions are used to “showcase” the upcoming drilling opportunities to management and hopefully lead to their funding and ultimately to new discoveries. The training I got throughout the chemical engineering curriculum when I had to write lab reports and make project presentations stood me in good stead. One class in particular that helped was a technical communication class that stressed verbal and written communication skills.

- **Providing Technical Support to My Mentor with Regard to Computer Applications.** For example, I created a spreadsheet that evaluated three different methods used for volumetric calculations and selected the optimum for each particular application. I was able to do this as a result of a computer course designed to introduce the chemical engineering student to programming in applications such as Excel, Mathematica, and FORTRAN.

The internship also exposed me to some of the issues that Bill Campbell mentioned in the first part of this article. First, virtually all of the work was team-oriented. It involved participating in meetings with geologists, geophysicists, and managers who usually averaged at least fifteen years of experience on the job. This meant that I had to find my niche in the group in order to become an effective contributor rather than a burden. Also, since most of my day-to-day tasks involved working with Bill, I had to become acclimated to his work routine and style. This was the first time I worked alongside someone for an extended period since most projects I had been involved in at school were of a shorter length and did not require more than a couple of hours per day of interaction.

Second, the internship gave me the chance to explore the “gut-level” questions Bill raised. All students at one point or another ask themselves these questions, and the best way to find the answers is through experience on the job. The four summers I worked at Apache, along with this past summer at 3M, have been an enormous help in my personal search for the answers. I realized I wanted to work in an office environment that requires team interaction and some travel and that involves work in the energy industry. With this “road map” in hand, I was able to narrow my job search to those compa-
Pneumatic Transport Studies

Pneumatic Conveying Loop

The pneumatic conveying system consists of a 14.5-m long, 52-mm I.D. horizontal copper pipeline with a 2.2-m long vertical section, a return line, T-bends, and several transparent sections placed along the pipeline. A regulated compressed-air supply provides the gas at the pressure necessary to convey the solids. A hopper placed on a scale and connected through flexible connections to the collector and feeder is used to continuously weigh the solids inventory. A solids collector consists of a paper filter bag placed at the top of the hopper. A gate valve is used to deliver the solids from the hopper, and different settings can provide various flow rates of the solids. The transparent sections allow visual observation of the flow patterns. Morris couplings are used to seal the connections and to keep the pipeline aligned (see Figure 4).

Wedge Construction

The wedge-shaped container was constructed of two pieces of clear Plexiglas (76-cm high, 74-cm wide, 0.4-cm thick). These were bolted to two steel supporting legs. Four bolts (1.27-cm diameter, 0.96-cm long), two to each leg, were used to attach each plastic sheet to the supporting legs. The front plastic piece was scribed so that it had a 1-by-1-cm grid network across the entire area. The grid network formed a convenient transparent graph for readily obtaining the position of the black marker beads in the bed. The width of the wedge, i.e., the distance between the Plexiglas faces, was 1.61 cm. Two brass rectangular bars (83.0-cm long, 1.61-cm wide, 2.54-cm thick) were used to form the inclined surfaces of the wedge. The surface of the brass bar adjacent to the glass beads was machined to be flat, with a tolerance of ±0.05 mm. The brass bars were taped to take eight brass screws (0.63-cm diameter, 0.96-cm long) on each side of the bar. These screws were used to fasten the bars to the Plexiglas at any desired inclination. A thin Plexiglas strip (76-cm long, 1.61-cm wide, 0.64-cm thick) was then placed on each machined brass bar surface to form the slide surface for the beads.

A vertical plastic disengaging section (6.35-cm high, 15.3-cm wide, 1.61-cm deep) was located at the bottom of the sloping sides of the wedge. The disengaging section was included to even out velocity gradients that could have been generated by the flow of beads through the slot located at the bottom of this section. The slot was adjustable and was made of two pieces of steel (17.0-cm long, 2-cm wide, 0.16-cm thick) that were attached by means of screws to the vertical front and back Plexiglas walls. The edges of the steel pieces that formed the slot were machined within ±0.05 mm to ensure perfect mating when the edges met. The slot opening was set with feeler gauges so that the opening was uniform to within ±0.05 mm across the width of the slot. The gate was closed with a piece of tape simply by attaching the tape to the front plastic wall. To start the flow of beads, the tape was removed and the gate fell open, permitting the solids to flow. The legs supporting the wedge had adjustable leveling screws mounted underneath them. These leveling screws were used to align the equipment vertically and horizontally. It had been shown that unless this equipment was perfectly aligned, it was impossible to obtain symmetrical velocity profiles.\[4\]
MATHEMATICAL POWER TOOLS
Maple, Mathematica, MATLAB, and Excel

JUDITH G. MACKENZIE, MAURICE ALLEN
University of Canterbury  •  Christchurch, New Zealand

The concept of using computers to help solve mathematical and computational problems has a particular appeal to engineers. Prior to the appearance of personal computers, programs were coded in a computer language, often FORTRAN, for a very specific application. Later, generalized packages were developed to solve problems in particular disciplines. Some were purely calculational, to solve differential equations or to invert matrices; others had more of an engineering flavor. Such specialized engineering software was powerful, but had a narrow focus; for example, there were programs for electrical circuit design, civil engineering structural calculations, or flowsheeting programs for the design of chemical processing plants.

Software programs with a strong emphasis on calculation and numerical evaluation continue to be marketed for the personal computer. Reviews of individual packages outline the latest features; for example, Maple V, Release 3,[1,2] Mathematica 3.0,[3,4] MATLAB 5.0,[5-9] and Excel 7.0.[10] Comparisons of some of these mathematical packages for science and engineering education have been made by Seiter[11] and Pattee.[12]

Two reports on the teaching of first-year undergraduate calculus courses, using Mathematica, give favorable outcomes.[13,14] Both courses are entirely computer based, online with interactive text, and students have access to many examples. Students see calculus as a course in scientific measurement, calculation, and modeling through the use of technology. “Technology also make it possible to present the subject as a highly visual, often experimental, scientific endeavor.”[15]

When using Mathematica for teaching chemical engineering concepts in process control and reaction engineering, Dorgan and McKinnon[16] found that students had mixed but generally positive reactions to its use. Several articles featuring the use of symbolic algebra computing in control engineering were published recently to foster a greater awareness of the potential offered to engineers by environments such as Mathematica and MATLAB.[17,18] Munro[17] empha-
sized that there are many areas where symbolic computing can offer significant improvements in the reliability and accuracy of results obtained.

This article is concerned with these mathematical power tools and will investigate general-purpose computer applications for mathematical calculations and symbolic algebraic manipulation. Their comparison and evaluation will be from the viewpoint of an undergraduate engineer seeking to solve mathematical problems quickly and reliably and to communicate results. A direct comparison of each package with the others will be given for each of the problems posed.

MATHEMATICAL TOOLS

Maple™ performs computations that include symbolic algebra and numeric approximations, linear algebra, calculus, trigonometry, differential calculus, infinite and indefinite integration, modeling, statistics, and graphics, and produces program statements for a FORTRAN compiler. It is a symbolic manipulative language that clearly displays algebraic expressions especially useful for integration and differentiation.[19] Barker considers Maple to be more powerful than Mathematica when it comes to solving complex physics problems.[20]

Mathematica™ combines numerical calculations and symbolic manipulations into an interactive environment, coupled
with graphic visualization and a high-level programming language. The program is divided into a kernel, which does the computation, and the front end, which provides the user interface and input capabilities. Mathematica equations are stored and can be imported or exported in ASCII format, favoring high portability. The Mathematica interface enables users to organize text, graphics, computer output, and pictures in a single ‘notebook.’ Included with Mathematica are standard functions and add-ons that allow the advanced user to perform more complex mathematical analysis.

MATLAB™ is an interactive, matrix-based system for scientific and engineering numerical computation and visualization.[21] The program operates with scalars, vectors, and matrices from expressions entered by the user. A variety of built-in functions can be used for displaying two- or three-dimensional color graphics. The basic MATLAB package may be extended with any of the different tool boxes designed for engineering specialties such as systems identification, optimization, control, spines, and Simulink. Electrical engineers like MATLAB because it is matrix-based and particularly suited for signal processing, digital communication, and control-system design.[22] A symbolic mathematics option in MATLAB uses the Maple kernel that extends its numerical capabilities to algebraic manipulation.

Excel™ is a popular spreadsheet with limited symbolic capability, but it is effective for small engineering calculations. The wide range of built-in mathematical and statistical functions, the ease of interactive programming, ease of reuse and modification, rapid graph generation, and on-line help make it an efficient design and prototyping tool. Although Excel was designed for business purposes, it is a practical tool for scientists and engineers.[23]

ENGINEERING PROBLEM SOLVING

To evaluate and compare the usefulness of these mathematical tools for teaching engineering problem solving, four engineering problems were solved using each of the four mathematical packages. Engineering problems considered were

- The calculation and graphical display of a heat-transfer calculation
- The inversion of a large matrix as part of input-output economic analysis
- A root-finding calculation for control-system design using the Bode stability criterion
- The solution of a set of ordinary differential equations to evaluate the quality of the control-system design.

PROBLEM 1
Two-Dimensional Heat Transfer

The two-dimensional steady-state conduction equation can be discretized on a rectangular grid to relate the temperature at any point to the temperatures at its four adjacent points.[24]

\[
T_{i,j} = \frac{T_{i-1,j} + T_{i+1,j} + T_{i,j-1} + T_{i,j+1}}{4}
\]

(1)

If the temperatures on the boundary are specified, then this equation can be used to iteratively calculate the temperatures at all points within the boundary. The rectangular configuration of a spreadsheet conveniently conforms to this formulation. Figures 1 and 2 show the temperature distribution of a square plate, all boundaries at 0°C except for a half of one edge, unsymmetrically placed, at 100°C.

The results and graphs were generated in Excel in about 40 minutes. The programming capabilities of MATLAB and Mathematica were used for the same calculation, but more than twice the time was required for the programming. The temperature results were easily and effectively graphed in Excel, MATLAB, and Mathematica. Graphical representation facilitates the problem solving and verification process, and color variation helps students to visualize the problem solution.
Energy analysis is a tool to determine how much of an energy resource is required to enable a given good or service to be produced and delivered to its consumer, enabling a physical description of the operation of a real-world process to be formulated. Input-output analysis can be used for analyzing the energy and environmental consequences of consumption. Pee[26] gives an example of energy analysis using 80 sectors.

Mathematically, the problem was that the data was available in the matrix form

\[ X = AX + Y \]  
(2)

where \( X \) and \( Y \) are vectors of system inputs and outputs, and \( A \) is the technical coefficient matrix. But the system was to be analyzed in the form

\[ X = (I - A)^{-1} Y \]  
(3)

where \( I \) is the identity matrix. Computationally, an 80-by-80 matrix was required to be subtracted from the identity matrix and inverted. The matrix was easily inverted with Mathematica and MATLAB, but Excel was unable to handle such a large matrix. It was important, however, to have the data in the correct format before importing.

The data was saved as plain ASCII text and imported into Mathematica with

```mathematica
mymatrix = ReadList["c:\excel\energy.dat", Number, RecordList -> True]
```

and into MATLAB with

```matlab
load c:\excel\energy.dat
```

Maple has a "read" function for importing data, but the large matrix data was unable to be imported into Maple.

After solving a large system of linear equations, an estimation of the condition of the computed solution is important for verification of numerical accuracy. Maple and MATLAB have functions to estimate the condition number of the inverted matrix to provide this verification[26]. The condition number of the matrix in the example above was 9.8, indicating that the inversion was relatively accurate and resulting in the loss of only one decimal place of significance.

An ideal proportional-integral-derivative controller, having the Laplace transform,

\[ \bar{m} = K_c \left(1 + \frac{1}{Ts} + Td s\right) \bar{e} \]  
(4)

where \( m \) and \( e \) are the valve position and error, \( K_c \) is the proportional sensitivity, and \( T_i \) and \( T_d \) are the integral and derivative times, was to be designed for the fourth-order process (see Figure 3)

\[ \bar{c} = \frac{1}{(T_s + 1)(T_i + 1)(T_d + 1)} \bar{m} \]  
(5)

where \( T_s, T_i, T_d \), and \( T_c \) are time constants. The Bode stability criterion[27] requires solution of the equation

\[ F(x) = \pi - \tan^{-1}(T_i x) - \tan^{-1}(T_d x) - \tan^{-1}(T_c x) \]

\[ -\tan^{-1}(T_i x) + \tan^{-1}(T_d x) - \tan^{-1}(T_c x) = 0 \]  
(6)

for the angular frequency, \( x \). This numerical approach, coupled with the calculation of the amplitude ratio, replaces the well-known graphical procedure[27] using the Bode diagram graph paper.

This root-finding problem was successfully and quickly solved by each of the four applications. The dialogue with Mathematica, with the output indicated, is shown in Figure 4.

Excel was used in two ways for this problem. First, a Newton root-finding method was derived by hand, taking about 50 minutes to derive and verify the derivatives. Each
successive iteration was a row of the spreadsheet. Alternatively, when the “goal”-seeking command was used, only 5 minutes were required, similar to the time required for any of the other applications. But in the full-design procedure, the root-finding had to be repeated three times, with only minor modification. Each of the applications supports the construction of user-defined functions, similar to functions, procedure, or subroutines in procedural programming languages.

**PROBLEM 4**

**Differential Equation Solution for Time Response**

The control system design in Problem 3 had the form shown in Figure 3. Problem 4 was concerned with the response of this system to a change in set point, r, or to a disturbance, u, in order to confirm the control-system design.

Differences between the nature of the mathematical applications became more evident when solving this problem. Maple and Mathematica provided the simplest solution. The relationships defining the closed-loop transfer function were defined and solved automatically for the Laplace transform of the process variable, c. The inverse Laplace transform function available in both Maple and Mathematica gave the required time response within an elapsed time of 5 minutes. The Mathematica notebook dialogue and response are shown in Figure 5.

A finite difference approach could have been taken in MATLAB and one of its differential equation solvers (ODE23 or ODE45) used. But since the problem was linear, the closed-loop transfer function was rewritten in state space form, and the matrix exponential function was used to calculate the time response.

The MATLAB m-file to set up the process matrix A, calculate its eigenvalues, and derive and plot the time response is shown in Figure 6. The algebra required 100 minutes, setting up the MATLAB calculation an additional 10 minutes, and the actual calculation and plotting about 10 seconds.

Excel did not have differential equation support. A solution was obtained by deriving the differential equation for the controller and each of the first-order elements from its transfer function and using a finite difference approximation to provide a recursive relationship (see Figure 7). Setting up
the spreadsheet took about 60 minutes and its calculation several seconds. Modeling the time response in this way enabled variables to be changed, giving an almost simultaneous change in the graph.

EVALUATION

Attributes of the mathematical packages were rated on a one-to-five-point scale (one being the worst and five the best) to assess their scope, intuitiveness, ease of use, graphics, and fitness for engineering applications; the results are shown in Table 1. All four of the packages are powerful problem-solving tools. In this evaluation, Mathematica was ranked ahead of MATLAB, with Maple following a close third and Excel fourth. But such comparisons are subjective and the differences between the packages were small.

CONCLUSIONS

The best application in a particular instance depends heavily on the nature of the problem. Maple had the advantage of giving a symbolic analytical solution, but did not have the numerical capabilities of Mathematica, MATLAB, or Excel. Each of the three “M”s dealt well with symbolic manipulation and graphics. Excel displayed the most flexible graphics with, for example, the capacity to easily rotate three-dimensional plots. The Mathematica notebook provided an excellent interactive feature for documentation, report writing, and teaching. The advantages of a particular application are lost if extensive work by hand is required to express the problem appropriately for that application.

Our opinion is that engineers need to be skilled in at least one spreadsheet such as Excel, a programming language, and at least one of the other mathematical packages. If an engineer is heavily involved in matrix manipulation and linear systems, then MATLAB has advantages, especially if its extensive optional tool boxes are relevant. Equally, Mathematica has distinct advantages in its use of a natural language, the “notebook” feature, and user interface. Maple was the most difficult package to learn and program, but was useful for verification of mathematical analysis.

The best tool depends on individual needs, and the time spent learning the applications will reap the benefits of these powerful mathematical tools. How to incorporate them into our graduate and undergraduate courses is a key issue for engineering educators.

REFERENCES

7. Foster, K.R., “Matrices and Much, Much More—MATLAB,”

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