Dianne Dorland  
Rowan College

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Dianne Dorland

Firmly Anchored . . . For Now

D.A. Barsotti

In her undergraduate days at South Dakota School of Mines and Technology, Dianne Dorland worked for the Institute of Atmospheric Sciences, first as the office “go-for” then as an undergraduate technician. She learned plenty about clouds, but even as she soared above, beyond, and through the nebulous matter—seeding clouds, collecting data, or studying nucleation in cloud systems—no one would quip that Dianne had her “head in the clouds.”

Today Dianne Dorland is Dean of Engineering at Rowan University, Glassboro, New Jersey. She is still soaring, still seeding, still seeking—but experiences have sharpened her vision and heightened her dreams. Today, as dean of Rowan’s innovative new engineering program, she is excited about the opportunity to develop and maintain strong links between engineering education programs and industry in a way that will benefit both the students and the region where she has just recently landed.

From drawing weather maps to charting new territory in chemical engineering education, Dianne has accumulated an enormous wealth of experience, both in her professional endeavors and in her personal undertakings. The sum of those experiences is obvious from the very first time you meet her.

THE HANDSHAKE AND THE PIPE WRENCH

When you first shake hands with Dianne Dorland, you know right away that she is a substantial person, says Gary Finley, a member of the Arrowhead Chapter of the
National Society of Professional Engineers in Duluth, Minnesota, where Dianne was an active participant. “She’s got a good grip.” Finley, who is technically retired from the engineering profession but consults and keeps active in his profession, had a chance to interact with Dianne when she headed the Department of Chemical Engineering at the University of Minnesota, Duluth (UMD). “Dianne is a professional engineer and a professional educator,” he says.

But it is that first impression that seems to best encapsulate what others find in Dianne.

Alan Nelson is a PhD candidate at Michigan Technological University. He had the opportunity to do his undergraduate studies under Professor Dorland’s watch. “When I arrived for the first day of class,” he recalls, “I quietly selected a seat in the back of the room to avoid unnecessary attention. I pulled my books out of my pack and adjusted my hat is such a way as to prevent eye contact with the instructor.” Instead of being an unknown in the back of the room, Nelson found he had captured the attention of the instructor. “Little did I know that she was not particularly fond of hats worn indoors, let alone baseball caps,” he says. “She politely asked me to remove my hat,” recalling that he did so with reservation. “I sat through the class with my hair protruding out in every direction,” he says, but he quickly realized that it didn’t matter because the instructor had a genuine interest in her students. “Dr. Dorland involved the students in a discussion—to learn about them and about their expectations for the course,’ he remembers. “By the end of the class, the instructor had earned my respect; a respect that continues to grow even today.”

“Dianne puts her students first,” says Ron Visness. Before, and even after, he retired from his position as manager of a research program for the State of Minnesota Minerals Division, Visness frequently worked with Dianne in her capacity as head of UMD’s Chemical Engineering Department. Even though Dianne’s calendar was full of administrative tasks, he says, she made sure she had time for the students. “She is also industry oriented and has a good feel for what industry wants and needs,” he comments, adding that students find that perspective valuable. “Dianne has been where they are going. She knows what happens when things go wrong in a chemical plant—and she knows the working end of a pipe wrench.”

A NEW VANTAGE POINT

Business incubator. Technology center. Industrial outreach. Student interaction. As dean of Rowan’s College of Engineering, Dianne is melding the experiences she’s had in her career to write the next exciting chapter on chemical engineering education. From her office in a state-of-the-art engineering building, she brings a unique vantage point to the chase. Her experiences will allow her to assess the needs of each of the partners—students, industry, and the community—that will be affected by Rowan’s innovative new engineering endeavor. “I can’t promise to deliver everything that everybody wants,” Dianne says, “but I have to find out what each of them wants, figure out what we can provide, and then determine what’s optimal for us and what’s optimal for our relationship.”

Several factors attracted Dianne to Rowan University. The engineering program, whose first class of engineers graduated in May 2000, was established with strong industrial interaction. This interaction is the basis for the clinic projects, the “hands-on, minds-on” clinic experiences that offer progressively more involved engineering situations for all four years of the program. In recruiting the faculty, the college sought forward-thinking candidates who had strong backgrounds and the potential to develop relationships within industry. When Founding Dean James Tracey set the course for Rowan’s College of Engineering, he was laying a foundation for the kind of engineers who would meet the challenges of the new millennium.

“This is a new educational experience,” Dianne admits. “It incorporates interaction between students in the different disciplines of engineering, between students in different class levels, between students in different industrial projects, between students and faculty. At Rowan, the first thing that freshman come to understand is that engineering is a state of mind.”

And that seems to be the state of mind where Dianne has taken up permanent residence. Though she has been settled in the dean’s office for just a short time, her presence fills the room. . .her hard hat, a congratulatory vase of long-stemmed red roses from a dear friend, and a calendar full of opportunity.

CHEMICAL ENGINEERING EQUALS FLEXIBILITY

Opportunities were not as apparent when Dianne was growing up in her South Dakota hometown of Belle Fourche. Nestled on the northern side of the Black Hills, the rural community of 4000 offered a solid education for its youth, but not many options. “There were few job prospects,” Dianne explains. “I could become a rancher’s wife or go to college.” Because of her aptitude in science and math, and her expo-
sure to engineering through her participation in the Junior Engineering Technology Society during those high school years, it was natural that Dianne chose to enroll in the engineering program at the South Dakota School of Mines and Technology. A strong recruiting effort for chemical engineers set the direction as Dianne began her undergraduate studies.

Dianne's youngest sister, Thais M'Annette Dorland Armstrong, recalls the beginning of Dianne's educational experiences. "I remember that when she went to college," she says, "there were so few women in attendance that she was forced to live off campus because there was no housing for female students."

"Engineering offered me a challenge," Dianne says. "I wasn't sure of the opportunity at the time, yet once on board, I knew it was a good fit for me." Dianne is a licensed professional engineer in the states of West Virginia and Minnesota, and will soon be licensed in New Jersey.

Dianne soon realized that rigors of the chemical engineering curriculum provided additional benefits. "I knew I had to work during my college years," she says, adding that since she knew there would be no financial support from her family, she would be paying her own way. Because of the demands of her studies, she quickly learned valuable skills—time management, communication skills, perseverance, and flexibility. Those same skills helped Dianne find and balance part-time jobs while she carried out her course load.

She had a number of interesting part-time ventures, ranging from bookkeeping to taking in ironing to house painting. "But the best job I had during that time was at the Institute of Atmospheric Sciences," she says. That’s where she had a chance to soar into a fair-weather adventure that has endured, trying her hand at everything from drawing weather maps to operating an instrument data-collection package at 10,000 feet.

Because of her position at the Institute while an undergraduate, Dianne was able to take some graduate courses in meteorology. "It was the flexibility of the chemical engineering department that allowed me to use funds from the Institute to complete my graduate studies," she admits, adding that the Department was willing to combine resources and curriculum with the Institute to make it possible for her to earn her Masters Degree in chemical engineering. Her fascination with clouds prompted her to minor in meteorology. "I am appreciative of the Department and the faculty," Dianne says. "What I owe them goes beyond words." The program at South Dakota is the model for what Dianne sees as a successful engineering program.

MODEL FOR A SUCCESSFUL ENGINEER

Much like the collaboration that takes place in a successful engineering program, so is there collaboration in the molding of an individual. And at this point in her life, Dianne can look upon inherited attributes, life lessons, and character-building moments to gain some perspective. There have been many mentors, friends, and family members who have made an impact on her, professionally and personally.

"On my mother's side, grandfather was a farmer who was fascinated with airplanes," Dianne recalls, thinking of her own interest in the weather and her passion for flying. "My grandmother Dorland lived with us, and when I was ten years old, she taught me to touch type using an instruction book with an 1898 copyright date," Dianne remembers, perhaps explaining her tendency to set goals, look ahead, and be prepared.

Dianne's father was an optometrist, and her mother stayed at home to raise the family. It was her parents' hope that all of their children would do more with their lives educationally. "My mom was the driving force in those efforts," Dianne says, relating one instance when her mom went into school to argue that Dianne be admitted into a drafting class.

Thais recalls Dianne's determination to set out in new directions. "One of my earliest memories in regards to career aspirations was when some friends of my parents were visiting. Being all of four years old, I was privy to their conversation, which turned to the subject of careers. I think the conversation sticks out in my mind because of the distinct shock on their faces when I piped in that I planned to get my masters degree in chemical engineering when I grew up. Of course, my aspirations and awareness were completely formed because of my older sister, Dianne."

Thais' relationship with Dianne has bloomed from sisterhood to best friend. "I admire Dianne for her strength, her ability to focus, her sense of clarity, and her desire to have fun in the process." Thais, who is a full-time artist, birdwatcher, and world traveler, says she is constantly aware
of the full emotional support of her oldest sister.

Those moments of family love weren’t always as obvious as the Dorland siblings were growing up. The second eldest of six children, Dianne found plenty of opportunity to practice conflict resolution, learning when it was wise to let go and when it was time to give in, when it was good to win and when it was okay to lose.

Dianne’s mother had quite an influence on her. Her mother read to the family and provided games for them to play. “We didn’t have a TV in our house,” Dianne says, adding that they did live next door to the library—“my second home.”

“My mother had an adventuresome spirit,” Dianne says. “I remember one time when she took a cigar box full of silver dollars, loaded us into the car, put the cigar box under the front seat, and headed out to have an adventure. When the box was half empty, we started the journey back home.” Her mother arranged many such journeys . . . to visit cousins, to go exploring, or to drive toward a sunrise. “She planted that spirit of adventure in me,” Dianne professes. “I learned to be to be spontaneous and flexible.”

NEW TERRITORIES - NEW ADVENTURES

It wasn’t long before Dianne had a chance to test her flexibility. Following an on-campus interview with Union Carbide in 1969, Dianne left South Dakota to join the company’s R&D department in South Charleston, West Virginia. Unfortunately, her job evaporated before she even arrived, due to a shift in the company’s economic situation. “I floated between several different departments,” Dianne remembers. “It was fascinating. I was exposed to a myriad of projects, and I began to see how flexible an engineer must be to survive on the job.” For a while, Dianne worked on a process for insulating the hulls of ships used to transport liquefied gases. She learned about problems with certain insulating materials and became aware of the health and safety issues that exist in the chemical industry.

After several other projects at Union Carbide, Dianne had a chance to move from textbook learning into the real world. “I worked on assessment of a butane oxidation process facility,” she explains. “This was the nasty core application of everything you learn in undergraduate school. It was no longer a simple problem, but a multi-component one—with all the by-products that occur in the commercial world.”

Another dose of reality hit when a company lay-off left Dianne out of work. Part of the lay-off targeted female spouses. Dianne, who, by then, had married a co-worker, was affected. Not wanting
to dwell on this, she summoned her energies and worked to get another job. She found success at a DuPont facility in Belle, West Virginia. She was hired as a process engineer, and provided technical support for operations in the plant. "I worked with Para Amino Cyclohexyl Methane (PACM), the chemical precursor to the fiber Qiana Nylon," she says. "It was an exciting time to be working at DuPont. The business was expanding and I got to work on the design and expansion of the process and to offer technical support during the start-up of the new equipment." Dianne was also responsible for providing quality control and dealing with the technical issues that were involved in the process.

Fortunately, there weren't too many issues with the fact that Dianne was the first full-time female chemical engineer at the site. "There was a period of adjustment for me and the plant," Dianne recalls, "but my supervisor, Dick Sherman, was more interested in my engineering talents than in my gender." A genuine bond developed between Dianne and her colleagues. A few years later, when Dianne took maternity leave for the birth of her first child, the plant operators found a special baby shower present for her. "They gave me a gift—prophylactics, with the admonition that I learn how to use them," Dianne says with a grin. "It was quite a compliment to know that they wanted me to come back to work—and not leave again."

**DIAPERS AND DECISIONS**

In 1975, Dianne resigned from DuPont and gave birth to her son Brad. Two years later, her daughter Decker was born. During their early years, Dianne stayed at home with Brad, who is now a PhD candidate in cell biology at Oregon State University, and Decker, who recently landed a full-time position as Program Assistant for the Greater Minneapolis Metro Housing Corporation.

While she was at home with her children, Dianne took an active interest in the community. She also found a part-time position in chemical equipment sales. In 1981, a teaching opportunity at West Virginia Institute of Technology became available and Dianne was hired to teach evening classes. She was eventually offered a full-time position as assistant professor. At some point during that time frame, Dianne realized that she wanted to pursue her PhD, and in the spring of '83, she headed to West Virginia University.

A grant for non-West Virginia undergraduates that was available through the Department of Energy took Dianne down new paths. She worked with Al Stiller on a novel method for processing coal. "I took note of Al’s interactions with government agencies and of the political involvement in funding," Dianne says. Not only did she find the process of coal extraction quite interesting, but she also became aware of the intersection between academics and politics.

"I attended graduate school with Dianne from 1983-1985," says David Bernemann (now Engineering and Math Instructor at North Iowa Area Community College) "and have maintained my friendship with her since that time. I think of Dianne as one of the smartest people I know." Bernemann acknowledges that Dianne has reached a high mark academically, but he is more impressed that she knows what is really happening in the world.

Phillip Kneisl is another of Dianne’s friends from graduate school. He is currently a Senior Chemical Engineer at the Schlumberger Reservoir Completions Center in Rosharon, Texas. From his experiences, he feels that a strong academic background is only part of the formula for a good engineer. "Dianne knows her technical limits," Kneisl says. "She is on good terms with everyone. She practices good politics. And she is always positive." Bernemann continues, "Dianne seems to be extremely effective at facilitating other people to do their best. This means that she is able to provide those around her with the resources to accomplish their goals. I think she gains personal satisfaction in assisting others with their accomplishments."

**DOWN TIME**

As friends, Bernemann and Kneisl shared in some of Dianne’s non-academic pursuits. Kneisl remembers that Dianne’s house was always the center of non-academic activities for chemical engineering graduate students in Morgantown. "There were many memorable parties, weekend brunches, lunches and dinners—and general bull sessions," he says.

Bernemann reveals another side of Dianne. "When we were in grad school, Dianne had a private pilot’s license and her own airplane—a Cessna 172," he says. Bernemann was one of the grad students that went flying with her, and he recalls one instance that showed Dianne’s ingenuity. "The carburetor heat cable on Dianne’s plane broke. (She did many of her own repairs on the plane.) She was going to buy a new cable but found out it cost something like $120," Bernemann says. To Dianne, the cable looked like a lawn mower throttle cable. "So she decided to replace it with a lawn mower throttle cable," he continues. "She asked me to help her with the repair. First we went to a local auto parts store and bought the lawn mower cable, then we went to the airport to make the repair." Bernemann admits that a Cessna 172 is a pretty simple machine, so the repair was pretty straightforward. He knew that the lawn mower cable was the same as the carburetor heat cable—without the large markup. What surprised him was Dianne’s insistence that since he helped with the repair, he should take the first flight with her. Bernemann was not surprised at Dianne’s love of adventure, but he found it impressive that she wanted to encourage that sense of adventure in others.

Dianne completed her PhD in chemical engineering in the fall of ’85. It had been a fairly tough haul, including an emphasis in environmental engineering. She felt she needed
an escape. Leaving her Cessna behind, she turned to her scuba diving and discovered a passion for the underwater world. She spent some time diving in the Red Sea and then toured the exotic lands of the Near East.

EDUCATION—REDESIGNING THE PROCESS

When Dianne returned, she worked for the Department of Energy while she looked for an academic position. In 1986, she heard of a new program being initiated at the University of Minnesota, Duluth (UMD). She remembers thinking that her varied background could be an asset to this new program. At UMD, Dianne was able to both teach and initially work as an environmental engineer for Sea Grant, an extension program at the university.

In the following years, Dianne worked her way through the ranks at UMD, becoming a full professor and head of the chemical engineering program. She had an immediate impact on the new department. Linda Deneen (currently Director of Information technology at UMD) first met Dianne when she became the head of the Department of Chemical Engineering. She adds her observations about one of her closest friends: "Dianne is a professional collaborator and team builder. She’s the one who brings groups of researchers together and paves the way for them to be successful as a team. She is also an excellent teacher."

Dianne left UMD with a very strong Chemical Engineering Department, one that was ranked second in US News and World Report this year. Dianne is proud of the program’s success. “I credit the wonderful people who gravitated to our program,” she says.

Richard Davis, Associate Professor in the UMD Department of Chemical Engineering, comments that much of that credit reflects Dianne’s goals for engineering education. “She was able to see the big picture,” he says, noting that Dianne wanted to move the department forward as a group of faculty—instead of as individuals. “She constantly looked for ways to share her contacts, research projects, funding opportunities, and professional development experiences.”

Gary Finley cites more evidence of Dianne’s positive impact on the students and the region: “In the past five years, 95% of UMD’s chemical engineering students took and passed the fundamentals test. When the national average is 70%, it speaks volumes about Dianne’s effectiveness in challenging those students.”

“Dianne brings out the professionalism in her students,” Finley observes. “Industries in the region are tickled with her students. They come in ready to go to work. Twenty-five percent never leave the Arrowhead, and twenty-five percent never leave Minnesota. The local folks appreciate that.”

That local impact, and that professional quality in Dianne and in her students, made her an impressive candidate for Rowan’s Dean of Engineering. According to Ralph Dusseau (Professor and Chair of Civil Engineering), Dianne was highly regarded by the Search Committee, by Rowan University President Donald Farish, and by Henry Rowan, the man who made the school of engineering a reality with the establishment of a $100 million endowment. “Dianne definitely had the best industry background and the greatest potential for establishing effective industry contacts for the College of Engineering,” continues Dusseau. “To use a sports analogy, Dianne hit a grand slam.”

CHARM AND WIT AND A MISSION

That professional quality hasn’t gone unnoticed by Ted Schoen, Dean of Rowan’s Business School. “Dianne is really willing to reach out, to make sure that our ideas for a proposed business incubator are right for our university,” he says. He has been traveling around the region with Dianne, visiting other incubators to learn how they operate. “Dianne has a way to get us thinking about the issues,” he says. “She is willing to share her expertise, she has a lot of energy, and she has a great sense of humor.”

Dianne brings a wide range of expertise to her new position. An array of published works and presentations illustrates her commitment to the environment (pollution prevention and industrial waste management), her dedication to the education of twentieth-century engineers (curriculum topics and student outreach proposals), and her knowledge of the role of engineers in industry. Her affiliation with professional societies like the AIChE, ASEE, and SWE is underscored by her prominent and active leadership positions.

“This is the fastest growing region in the state,” says Stewart Slater (Professor and Chair of Chemical Engineering at Rowan). He surmises that as Dean, Dianne will be able to have an important impact on the advancement of industry in the area. But it is Dianne’s mission in chemical engineering education that really interests Slater and the other members of the engineering faculty. They feel that her focus on students, on the links with industry, and on the intersection of the classroom and the real world will advance chemical engineering education at Rowan University.

Dianne Dorland has come to the Garden State. She zips around her eight-acre rural tract on her little green garden tractor, wearing a wide-brimmed garden hat and earplugs. She tends to the blueberries and studies nature at the edge of her pond. She plants the seeds and waits for the harvest. The life is bountiful and rewarding.
The University of Melbourne has a reputation as being Australia's leading research university, attracting more competitive research funds than any other university in the country. Likewise, the Chemical Engineering Department at Melbourne is recognized as one of Australia's leading departments in terms of both its research and its teaching.

The city of Melbourne, with a population of some three million people and located in the southeastern corner of Australia, was founded in 1835 by settlers who moved there from the first settlement in Sydney. It prospered when gold was discovered some 110 km to the west in the 1850s, and by 1861 it had become the largest city in the country as a result of the influx of immigrants eager to try their luck in the goldfields. In 1901, Melbourne became the temporary capital of the newly independent country of Australia and it soon became the manufacturing base of Australia. Following World War II, European immigrants brought diverse cultures to the city, and in 1956, it became known around the world as the home of the Olympics. Decades later, a second wave of immigrants, mainly from neighboring Asian countries, again enhanced the culture of the city. Home to major sporting events and superb restaurants, Melbourne has repeatedly won accolades as being the "World’s Most Livable City."

The University of Melbourne became Australia’s second university when it was founded in 1853. The University’s motto, “Postera crescam laude” is often rendered as “Growing in the esteem of future generations.” Its mission is to make the University of Melbourne one of the finest universities in the world. It is located just one kilometer north of the downtown area and is a broad-based university with faculties of architecture and planning, arts, economics and commerce, education, engineering, law, medicine, music, science, and veterinary science. The university has over 34,000 enrolled students, including over 9,000 graduate students, and over 2,100 academic staff members. It is a founding member of the Universitas 21 international consortium of universities.

The first engineering degree was awarded in 1883. Since then, the University has played a leading role in the education of generations of professional engineers in Australia. In more recent times, the University has established a reputation for excellence in the Asia-Pacific region, attracting increasing numbers of international students to its various engineering disciplines. The university offers degree programs in chemical engineering, civil engineering, computer engineering, computer science, electrical engineering, electronic engineer-
ing, environmental engineering, geomatics, manufacturing engineering, mechanical engineering, mechatronics, and software engineering.

The Chemical Engineering Department is one of the largest in Australia, with more than 600 undergraduate students currently enrolled in its courses. In addition, more than 80 students are presently enrolled in its postgraduate programs. Women represent nearly half of the undergraduate population, one of the highest proportions of any engineering department in Australia.

THE UNDERGRADUATE PROGRAM—THE MELBOURNE PARADIGM

Flexibility is the key word that describes the undergraduate chemical engineering program at Melbourne. It is this flexibility that allows the majority of the students in the Department to enroll in not one, but two, undergraduate degree programs.

Until the late 1980s, the four-year structure of the chemical engineering degree was very rigid. The subjects and the sequence in which they were to be studied were prescribed. Students studied the basic sciences of mathematics, chemistry, and physics. In their first year they also received general engineering education across the other major engineering disciplines, and over the last three years of the course they undertook studies in chemical engineering science, practice, and design. They also studied process economics, management, and engineering law.

Occasionally, permission was given for students to take one or two non-engineering subjects, allowing them to pursue some other interest. These subjects were taken either in addition to their normal study loads (i.e., as an overload) or in lieu of certain specified subjects. If the student wished to complete two degrees, then there was no alternative but to pursue them consecutively. Usually some credit was given toward the second degree for work performed in the first degree. For example, a student who had completed a three-year Bachelor of Science (BSc) degree might be given one year of credit toward a four-year Engineering (BE) degree. This would reduce the total time taken to obtain both undergraduate degrees from seven years to six years.

Beginning in the late 1980s, students were permitted to pursue two degrees simultaneously. By taking extra subjects in each semester and by spreading the content of both degrees over the entire time, it became possible to achieve a reduction in the time required to complete the requirements of both degrees. For example, instead of taking seven years to complete studies toward undergraduate degrees in engineering and commerce, it became possible to gain both degrees in only five years. The workload required to accomplish this feat, however, was very heavy, with overloads required in every semester. Only students with demonstrated abilities were permitted to enroll in concurrent degrees.

In 1990, the first combined-degree program involving chemical engineering was introduced when the combined Bachelor of Engineering/Bachelor of Science (BE/BSc) program was offered. Its structure made it possible for a student to meet the requirements of both degrees in just five years. The reduction in the time required to complete two degrees is achieved by the existence of material common to both degrees, e.g., chemistry and mathematics. It should be noted, however, that it is not possible to obtain a BSc degree by simply studying for an additional year after completing the BE degree. Study for the two degrees must be integrated from the moment the student enters the University.

The Bachelor of Engineering/Bachelor of Arts (BE/BA) combined degree program was introduced in 1992, allowing students to pursue an interest in a language, history, or other

... the University has established a reputation for excellence in the Asia-Pacific region, attracting increasing numbers of international students to its various engineering disciplines.
popular science majors are the biological-based sciences, biochemistry, and microbiology. In more recent years, the study of pharmacology and genetics has become popular with the BE/BSc students. Other science disciplines that combined-degree students have enrolled in include biology, botany, computer science, geology, psychology, and zoology.

Of the BE/BA students enrolling over the same period, more than 80% have undertaken a language as their Arts major. Other majors include criminology, fine arts, history, linguistics, politics, psychology, and women's studies. The diverse nature of studies chosen by the students is indicative of the flexibility of these programs.

BE/BCom students are able to enroll in commerce subjects ranging from microeconomics to accounting and from personnel management to international trade. BE/LLB students often choose to complement their chemical engineering studies with subjects such as corporate law, corporate governance, and international law.

In a recent survey of the future directions for chemical engineering education, James Wei suggested that it was time for chemical engineering educators to seek a new paradigm. He suggested several possibilities that would empower engineering graduates to meet the challenges of the new century. Should chemical engineering become more oriented toward perceived societal needs such as environmental protection, manufacturing efficiency, and sustainability? Should it move to embrace developing disciplines as exemplified by information technology, nanomaterials, and tissue engineering? Should the educational processes focus more on people, teamwork, leadership, and communication skills? Should it broaden to more hybrid degrees of financial engineering? Or should chemical engineering education focus not so much on the design of new processes, but more on the development of new products?

As in any industry, chemical engineering educators must also consider the demands of their clients, namely their students, the processing industries, and the chemical engineering profession. In the last two decades of the 20th century, the petrochemical industries, traditional employers of chemical engineering graduates, cut back their graduate recruitment programs. In order to find employment, graduates began to consider the opportunities in non-traditional industries such as food, finance, and pharmaceuticals. Can the search for Wei's new paradigm and the changing requirements of the clients be answered in a single development?

At the University of Melbourne, we believe that our extensive combined-degree program is possibly the new paradigm. While no single engineering program can produce chemical engineering graduates at home in all the emerging areas from tissue engineering to intelligent processes, the chemical engineering graduates take with them into the work place understanding and expertise in a range of disciplines. This is the Melbourne paradigm.

The Department also has an excellent record in teaching. Every year the Graduate Council of Australia surveys graduates from all universities across all technical and non-technical disciplines. Using the responses to twenty-four questions, each teaching department in the country is given a score for several different categories. The survey of 1998 graduates showed that Melbourne's Chemical Engineering Department was one of the top departments in its discipline. It ranked second among the ten Australian chemical engineering departments on the Good Teaching and Clear Goal scales and in terms of overall satisfaction with the course.

International exchange is also a feature of the undergraduate program. As a member of the Universitas 21 consortium, the Department has a number of undergraduate exchange programs in place with leading universities around the world. These programs generally permit our students to spend up to twelve months at a foreign institution, usually in their third year. Each year the Department also has a number of study-abroad students from around the world who come to the university for a single semester. These students are always welcome.

**RESEARCH**

The Department is one of Australia's leading chemical engineering departments in terms of research. In 1998 it had the highest competitive-grant research income of any Australian chemical engineering department (with an income of more than $217,000 per full-time equivalent staff member) and published more papers per government-funded staff member than any other Australian chemical engineering department. The research activities of the Department are diverse and are focused principally around the three research centers

- The G.K. Williams Cooperative Research Centre for Extractive Metallurgy
- The Particulate Fluid Processing Centre, a Special Research Centre of the Australian Research Council
- The Cooperative Research Centre for Bio Products

The centers are at the forefront of international research and are the outward face of the Department's research expertise. Supporting the centres is a fundamental research infrastructure comprising: non-Newtonian fluid mechanics, high-temperature thermodynamics, separation processes, and computational fluid dynamics. Other research areas of significance are biochemical engineering, environmental engineering, fluoride process engineering, development technologies, pulp and paper, and, more recently, polymer science and mineral processing.

The G.K. Williams CRC for Extractive Metallurgy creates new, technically competitive advantages for the Australian smelting industry based on enhanced smelting proficiency.
It was established in 1991 as a joint venture between the Commonwealth Scientific Industrial Research Organization (CSIRO) and the University of Melbourne. Research is focused on high-temperature processes involving both fundamental and applied research, with world-class research capability in measurement and modeling of thermodynamic and transport properties of solids and melts at high temperature, physical modeling of high-temperature operations, flow visualization, and laser flow diagnostics and computational fluid dynamics of multi-phase complex flows. Many research achievements have resulted in improved technical and economic performance for industry, including a licensing agreement with major international companies to commercialize a new patented concept and design of composite refractory cooling systems.

The Particulate Fluids Processing Centre (PFPC) develops key science for the processing of particulate fluids of all kinds, concentrating on systems involving solid and liquid particles where the dispersed phase is colloidal in nature. Through the coordination of proven international strengths in surface chemistry, continuum mechanics, and non-Newtonian fluid mechanics, the PFPC effectively solves particulate fluid processing problems experienced by the agricultural, chemical, food, inkjet printing, mineral, water treatment, waste management, ceramic, and pigment industries.

The Cooperative Research Centre (CRC) for Bio Products is a collaborative venture with three participants: The University of Melbourne (Botany School and Chemical Engineering Department), CSIRO, and industry. Professor David Boger leads the Department’s participation and heads the Fundamental Testing and Hydrocolloids node of the CRC. The main goal is to “establish the science and technology underpinning the manufacture of plant biopolymers for the food and other industries.” Research of the group is focused toward understanding the fundamental structure-function relationships of biological molecules directed at applications. The key fundamental research areas are understanding the adsorption to and stabilization of the oil-water interface using biopolymers and the rheology and gel behavior of these systems. Fundamental programs include rheological characterization of novel gelling biopolymers for new material
ACADEMIC STAFF
Chemical Engineering Department, University of Melbourne
Melbourne, Victoria 3010, Australia
Phone: +61 3 8344 6631  Fax: +61 3 8344 4153  Web: http://www.ecr.muct.au/%7Echemengl

■ Professors

- **David Boger** is Laureate Professor of Chemical Engineering and Director of the Particulate Fluids Processing Centre. He is also a Program Leader in the Cooperative Research Centre for Bio Products. His research is primarily in non-Newtonian fluid mechanics, with interests ranging from basic polymer and particulate fluid mechanics to applications in the minerals, coal, oil, food, and polymer industries. The winner of many international awards, he has published nearly 300 papers and consults widely around the world.

- **Geoff Stevens** is Professor and Head of the Department. He has an international reputation in solvent extraction, interfacial phenomena, and emulsion stability and is presently Secretary General of the International Solvent Extraction Committee. His research is primarily in the hydrometallurgical field, but also covers aspects of food, pharmaceutical processing, and environmental or waste-water processing.

- **Jannie van Deventer** is Professor of Mineral and Process Engineering. He is the leader of the Mineral Processing Group. His research interests include diagnostic leaching of gold ores, extraction of gold by activated carbon, modeling of simultaneous leaching and adsorption processes, image analysis of flotation froth, transport processes in froth flotation, geopolymerization of waste materials, immobilization of toxic waste, and simulation of ill-defined processes using artificial intelligence.

- **David Wood** is Dean of the Faculty of Engineering and Professor of Engineering. He is the immediate Past Chair of the Institution of Chemical Engineers in Australia and a former Vice-President of the Institution of Chemical Engineers (UK). Over the last thirty years his research has ranged widely, but in more recent years it has focused on fluoride processes. He is presently Chair of the Sixth World Congress of Chemical Engineering, which will be held in Melbourne in September 2001.

■ Professorial Fellow

- **David Solomon** is a Professorial Fellow within the Department. He leads the Polymer Science Group and is best known in Australia as the leader of the research team that developed the plastic bank note, currently in circulation throughout Australia.

■ Readers and Associate Professors

- **Malcolm Davidson** is a Reader within the Department. Trained as an applied mathematician, his research interests include computational fluid dynamics in process engineering. Much of his current work is associated with the G.K. Williams Cooperative Research Centre for Extractive Metallurgy.

- **Neil Gray** is a Reader within the Department. After spending several years with BHP Central Research at Newcastle, New South Wales, he has continued his main research interest in the area of physical and mathematical modeling of rate phenomena in metallurgical processes. He is currently Program Leader in the G.K. Williams Cooperative Research Centre for Extractive Metallurgy. In conjunction with WMC Resources Ltd, a licensing agreement has recently been signed with major international companies to commercialize a new patented concept and design of composite refractory cooling systems.

- **Peter Scale** is a Reader in the Department. His research activities include understanding the measurement and application of compressional dewatering of solid materials and the rheological and electrokinetic characterization of concentrated suspensions of particles. Unit operations of interest include clarification, thickening, and filtration and an aim is to be able to predict and optimize these operations from first principles on the basis of laboratory measurements. Interests in the area of characterization of suspensions include the use of electroacoustics and the failure of concentrated flocculated suspensions of particles in shear.

- **Neville Pamment** is an Associate Professor of Chemical Engineering and leads the Biochemical Engineering activities in the Department. He is a Commissioner of the International Yeast Commission. His research interests range from ethanol production from lignocellulose using recombinant bacteria to the kinetics and physiology of product inhibition in microbial fermentations.

- **David Shallcross** is an Associate Professor and Universitas Fellow in the Department. His research interests include ion exchange and enhanced oil recovery. The author of two books, he is active in the secondary school community, developing teaching material aimed at raising the profile of the engineering profession among school students. He is also Chair of the Program Committee for the Sixth World Congress of Chemical Engineering and is Associate Dean (International) for the Faculty of Engineering.

■ Lecturers

- **Mike Conner** is Senior Lecturer and Deputy Head of the Department, responsible for all undergraduate matters. He is also a Deputy Director of the University’s Office of Environmental Programs. His research interests lie mainly in the areas of environmental engineering and policy and thermochemical biomass conversion.

- **Geoff Covey** is Senior Lecturer and is responsible for supervising the final-year design project. After a career in the pulp and paper industry spanning twenty years, he continues his research interest in this area. His other areas of interests include process development and economics and pan pelletizers. He is also a member of the fluoride research group.

- **David Dunstan** is Senior Lecturer and is a physical chemist by training who leads a team in the Cooperative Research Centre for Industrial Plant Biopolymers. His key research areas are understanding the adsorption to and stabilization of the oil-water interface using biopolymers and the rheology and gel behavior of these systems. Fundamental programs include rheological characterization of novel gelling biopolymers for new material design.

- **Leong Yow** is a Senior Lecturer and his research interests include non-Newtonian fluid mechanics, inverse problems in rheology, and hydrodynamic stability.

- **Andrea O’Connor** is a Lecturer whose research focuses on surfactant behavior and separation processes, particularly those for the food and pharmaceutical industries and for waste-water treatment. Mesoporous molecular sieves are synthesized and tailored for selective separations by adsorption via size exclusion and targeted surface chemistry. The current focus of this work is on the development of these materials for purification of high-value biological molecules.

- **Sandra Kentish** is a Lecturer and joined the Department in early 2000. She has a strong industrial background, with experience in the petrochemical, photographic, and paper industries, as well as in chemical-hazard management. She is developing research interests in a number of areas, including biopolymer processing, biofouling, solvent and supercritical extraction, carbon dioxide absorption from flue gases, and the use of ultrasonics in industry. Molecular dynamics simulation is another area of more fundamental interest.
design. Rheooptic, time-resolved fluorescence, and light-scattering measurements aimed at developing understanding of solution flow behavior are also studied.

Other research groups are also very active within the Department. The Separation Processes Group investigates rate phenomena involved in separation processes with particular reference to hydrometallurgy, waste treatment, and biochemical separations. A major focus is on gaining a better understanding of the interplay between diffusion, hydrodynamics, and the interfacial reactions occurring in solvent-extraction systems. In particular, novel techniques have been developed based on attenuated total internal reflectance spectrophotometry and, more recently, atomic force microscopy to study interfacial phenomena and reactions occurring at the interface. Mechanistic models for axial dispersion in pulsed sieve plate columns have been developed. In addition, the group has been active in liquid membrane processes, coalescence processes, diffusion in liquid systems, and in ion exchange. Biochemical separation processes being studied involve a range of operating and potential technologies for the food, pharmaceutical, and water-treatment industries. These include adsorption using specifically tailored adsorbent materials, electrophoresis, supercritical extraction, and ultrafiltration. Surfactant aggregation phenomena and their applications are also under investigation. Novel ion exchange processes presently being studied include ion exchange in radial flow and ion exchange equilibria in dual exchanger systems. Much of the work is in collaboration with others in the University, with the CSIRO Division of Chemical and Polymers, Tsinghua University Beijing, Massachusetts Institute of Technology, and with industry.

The Mineral Processing Group focuses on reactions at the fluid-solid interface. Electrochemical and mineralogical aspects of the extraction of metals from ores are studied at both laboratory and plant levels. Significant advances have been made in understanding the kinetics and equilibrium of the interaction between reacting and dissolving solids and the presence of adsorbents such as activated carbon and ion exchange resins. Various features of artificial intelligence have been integrated with systems of differential equations to describe the dynamics of operating plants, especially for cases where fundamental models are lacking. The transformation of reactive alumino-silicate wastes into useful construction materials is being investigated extensively at both laboratory and pilot-plant scale. Emphasis is placed on interfacial phenomena and the evolution of microstructure during the formation of geopolymers. This group succeeds in integrating fundamental research with the needs of operating plants.

The Polymer Science Group has interests in a diverse range of macromolecular related projects that combine the disciplines of polymer science and chemical engineering. The span of research includes phenolic resins and their composites; minimal shrinking monomers for specialty applications; novel multifunctional monomers for controlled network formation; grafting studies of polyolefins; development of living radical polymerization for the generation of predetermined macromolecular properties; and the determination of kinetics of propagation.

The Fluoride Process Engineering Group has special expertise in fluoride chemistry. Its work involves the treatment of minerals with fluoridating agents to produce pure products. It is also developing processes for the treatment of carbonaceous materials such as coal and spent pot-lining from aluminium smelting to produce commercial products. While some government support has been obtained, the group almost totally interacts with industry, both large and small, Australian and overseas. Currently it has three major projects: a new process for production of titanium oxide pigments; a process for the production of ultra-clean coal; and a process for the recovery of spent pot-lining.

The Computational Fluid Dynamics Group investigates fluid dynamics and transport phenomena in single and multiphase flows in process engineering. A major theme is the fundamental study of dispersed multiphase flows and two-fluid flows with deforming interfaces. Current topics include the dispersion of solids in metallurgical melts, molten slag foaming, droplet breakup, heat and mass transfer in soils, drop impact on solid surfaces and liquid films, slumping of yield stress materials, mass transfer at deforming interfaces, and self-sustained oscillations of confined jets.

The Biochemical Engineering and Fermentation Technology Group works on the application of microorganisms and enzymes to chemical processing. A major focus is on the use of recombinant bacteria to produce fuel ethanol from lignocellulosic materials such as wood and straw. The group also has an international reputation for its fundamental research on the factors affecting product inhibition in fermentations, the focus being most recently on the key role of acetaldehyde as an inhibitor or stimulant of yeast and bacterial alcohol fermentations, depending on the concentration of this metabolite.

THE FUTURE

The Department is one of the strongest research departments in the University. As its activities and student numbers have grown over the last two decades, it has gradually spread out from its original building built in the 1960s. In 2001, construction will begin on extensions to the existing building that will allow the Department much needed research space for expansion.

It is the success of the Department's graduates that continues to illustrate its success in chemical engineering education and research. In its ranks of graduates, the Department boasts three Rhodes Scholars and the current Australian Chief Scientist. Its future is assured by the continued success of its graduates.
COMBUSTION SYNTHESIS OF ADVANCED MATERIALS

The Union Carbide ChE Division Lectureship Award is bestowed annually on an exceptional engineering educator and is designed to recognize and encourage outstanding achievements in important fields of fundamental chemical engineering theory or practice.

Arvind Varma is the Arthur J. Schmitt Professor of Chemical Engineering at the University of Notre Dame. A native of India, he received his PhD degree from the University of Minnesota in 1972 and remained there for one year as an assistant professor. He was a senior research engineer with Union Carbide Corporation for two years before joining the Notre Dame faculty in 1975, where he achieved the rank of Professor in 1980 and his current Schmitt Chair position in 1988.

Dr. Varma’s research interests are in chemical and catalytic reaction engineering, and synthesis of advanced materials. He has published over 200 research papers in these areas and co-authored three books: Mathematical Methods in Chemical Engineering (Oxford University Press, 1997), Parametric Sensitivity in Chemical Systems (Cambridge University Press, 1999), and Catalyst Design: Optimal Distribution of Catalyst in Pellets, Reactors, and Membranes (Cambridge University Press, 2001).

He is also the founding Editor (1996-present) of the Cambridge Series in Chemical Engineering, a series of textbooks and monographs published by Cambridge University Press.

Varma served as Department Chair at Notre Dame during the period from 1982 to 1988. He has served as Visiting Professor at a number of institutions, including the University of Wisconsin, Caltech, and Princeton. He has received several awards for his teaching and research activities, including the R.H. Wilhelm Award (1993) of the AIChE.

ARVIND VARMA
University of Notre Dame • Notre Dame, IN 46556

Since prehistoric time, mankind has used exothermic reactions for its survival—for example, burning of wood for warmth and preparation of food. The energy from exothermic reactions has also been used to modify properties of materials. Thus it was discovered more than ten thousand years ago that heating a piece of clay in fire converts it into a ceramic with very different and useful properties. Modern technologists sinter net-shape bodies consolidated from powders in furnaces to produce, for example, ceramic shields to protect spacecraft. In both cases, the basic principle is the same: application of external heat to rearrange chemical bonds and shift the material properties in the desired direction. Since rearrangement of chemical bonds may release significant energy itself, however, it is attractive to use this energy directly to produce valuable materials. Such a method was discovered some thirty years ago and is called combustion synthesis (CS). Comprehensive reviews of this field are available in the literature,\textsuperscript{[1-3]} with recent achievements summarized in a popular account.\textsuperscript{[4]}

NATURE OF COMBUSTION SYNTHESIS

Let us introduce this process by considering fine (less than 100 micron, about the thickness of a human hair) powders to two metals: nickel (Ni) and aluminum (Al). Taking these powders in the appropriate ratio (e.g., Ni/Al about 2 by weight), we can mix them thoroughly and create an article with tailored form and shape by using a pressing technique. Next, one spot on the article surface is heated for a few seconds by, for example, a heated tungsten coil or laser beam. The reaction between Ni and Al starts at the hot point and propagates rapidly (about 10 cm/sec) along the volume of the article in the form of a bright glowing (combustion)
wave. In the wave, nickel and aluminum melt and react with each other to form (synthesis) an intermetallic compound, nickel aluminate (NiAl). Such intermetallics have a number of attractive characteristics, including low density, high corrosion resistance, high strength even at high temperature, and relatively low cost. For these reasons, NiAl-based materials are good candidates for demanding high-temperature applications, such as aircraft turbines and other engine parts.

Some advantages of the CS method over conventional powder metallurgy techniques of advanced materials production include low energy requirements, short synthesis times (on the order of a few seconds), high temperatures (2000-4000 K), and high heating rates (up to $10^6$ K/s), which allow one to produce unique (e.g., metastable) compositions. Also, owing to intensive volatilization of impurities at the very high temperatures in the reaction wave, the products of CS are frequently purer than the starting reaction mixture. In addition, there is essentially no limitation on size of the synthesized item, since the heat is generated not by an external heating device but by a chemical reaction that proceeds at every point inside the sample.

These characteristic features make CS different from conventional technologies, which usually take tens of minutes or hours at temperatures that can be achieved in common furnaces (usually less than 2000 K), and possess a non-uniformity of temperature (and hence properties) distribution along large-scale samples. Owing to the fact that CS technology has the potential to prepare advanced materials and net-shape articles in one step, and that it has extremely low external energy requirements, it is also well-suited for use on space platforms.

Efficiency of the method is not the only point of interest regarding this process, however. Even more interesting is the fact that under the unique conditions of CS, reaction kinetics, mechanism of reaction, and product microstructure formation become different from those realized under conventional isothermal or low-heating-rate conditions.

From the viewpoint of chemical nature, three main types of CS processes can be distinguished. First, gasless combustion synthesis from elements, where all initial reactants, intermediate, and final products remain in condensed (solid or liquid) state. For this reason, such reactions are sometimes called solid flame. The most popular examples are reactions of transition metals with carbon and boron, e.g.,

$$\text{Ta}^{(s)} + C^{(s)} = \text{TaC}^{(s)} + 146 \text{ kJ/mol}$$

$$\text{Ti}^{(s)} + C^{(s)} = \text{TiC}^{(s)} + 230 \text{ kJ/mol}$$

$$\text{Nb}^{(s)} + 2B^{(s)} = \text{NbB}_2^{(s)} + 175 \text{ kJ/mol}$$

The second type, called gas-solid combustion synthesis, involves at least one gaseous reagent in the main combustion reaction. Nitridation of titanium and silicon are common examples:

$$\text{Ti}^{(s)} + 0.5N_2^{(g)} = \text{TiN}^{(s)} + 335 \text{ kJ/mol}$$

$$3\text{Si}^{(s)} + 2N_2^{(g)} = \text{Si}_3\text{N}_4^{(s)} + 750 \text{ kJ/mol}$$

The third main type of CS is reduction (thermite) combustion synthesis, where metal or nonmetal oxides (e.g., Fe$_2$O$_3$, B$_2$O$_3$, TiO$_2$) react with a reducing metal (e.g., Al, Mg, Zr, Ti), resulting in the appearance of another, more stable oxide, and reduced metal. This reaction may be followed by the interaction of the formed reduced metal with other elemental reactants to produce desired products. An example of this type of CS is

$$\text{B}_2\text{O}_3^{(s)} + 2\text{Al}^{(s)} + \text{Ti}^{(s)} = \text{Al}_2\text{O}_3^{(s)} + \text{TiB}_2^{(s)} + 700 \text{ kJ/mol}$$

where TiB$_2$ is the desired product and Al$_2$O$_3$ can be removed (e.g., by centrifugal separation) and used separately, or a ceramic composite material (Al$_2$O$_3$ + TiB$_2$) can be produced.

In addition to the three main types of CS processes, there are two more recently developed types where the initial reactants are all in either gas or liquid phase, while...
the final products are in solid state and are formed by a fast propagating reaction wave.

In physical terms, there are two modes by which combustion synthesis can occur: self-propagating high-temperature synthesis (SHS) and volume combustion synthesis (VCS). In both cases, reactant powders are pressed into a pellet, typically cylindrical or parallelepiped in shape. The samples are then heated by an external source (e.g., tungsten coil, laser) either locally (SHS) or uniformly (VCS) to initiate an exothermic reaction. The characteristic feature of the more prevalent SHS mode is, after initiation locally, the self-sustained propagation of a high-temperature reaction wave through the heterogeneous mixture of reactants. Thus, the SHS mode of reaction can be considered as a well-organized wave-like propagation of the exothermic chemical reaction through a heterogeneous medium, followed by the synthesis of desired condensed products. During VCS, the second mode of CS, the entire sample is heated uniformly in a controlled manner until the reaction occurs essentially simultaneously throughout the volume. This mode of synthesis is more appropriate for weakly exothermic reactions that require preheating prior to ignition. A sequence of video frames of reaction wave propagation during CS of nickel aluminide by the SHS mode is shown in Figure 1.

**TYPES OF MATERIALS SYNTHESIZED**

Since the initial discovery of the process, the number of products synthesized by CS has increased rapidly and currently exceeds 500 different compounds. Specifically, these include advanced materials such as carbides, borides, silicides, nitrides, oxides, intermetallics, and their composites. Examples of these, along with their applications, are given in Table 1. Most of these compounds possess high heats of formation—this is the main reason why they can be produced by CS without external heating.

In general, methods for the large-scale production of advanced materials by combustion synthesis consist of three main steps:

- **Preparation of the green mixture**
- **High-temperature synthesis**
- **Post-synthesis treatment**

A schematic diagram of these steps is presented in Figure 2. The first step is similar to the procedures commonly employed in powder metallurgy, where the reactant powders are dried (e.g., under vacuum at 80-100°C), weighed into the appropriate amounts, and mixed (e.g., by ball mixing). For some applications, cold pressing of the green mixture is

![Sequence of video frames of reaction wave propagation during combustion synthesis of nickel aluminide by the SHS mode: (a) ignition, t=0; (b) 0.1s; (c) 0.2s; (d) 0.4s; (e) 0.6s; (f) complete reaction, 0.8s.](image)

<table>
<thead>
<tr>
<th>Composition</th>
<th>Chemical Formula</th>
<th>Examples of Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbides</td>
<td>TiC, ZrC, HfC, TaC, NbC, SiC, TiC-Cr₃C₉</td>
<td>Abrasives, cutting tools, ceramic reinforcements</td>
</tr>
<tr>
<td>Borides</td>
<td>ZrB, TiB₂, HfB₂, MoB, TaB₂, LaB₂, NbB₂</td>
<td>Abrasives, cutting tools, cathode</td>
</tr>
<tr>
<td>Silicides</td>
<td>Ti₅Si₃, Ti₅Si, MoSi₂, Zr₃Si, Zr₂Si</td>
<td>Heating elements, electrical connectors, Schottky barriers for electronics</td>
</tr>
<tr>
<td>Intermetallics</td>
<td>Aluminides of Ni, Zr, Ti, Cr, Co, Mo, Cu, etc.</td>
<td>Aerospace and turbine materials, shape memory alloys</td>
</tr>
<tr>
<td>Nitrates</td>
<td>TiN, ZnN, NbN, HfN, TaN, VN, AlN, Si₃N₅, BN</td>
<td>Ceramic engine parts, ball bearings, nuclear safety shields</td>
</tr>
<tr>
<td>Hydrides</td>
<td>TiH; ZrH; ZrNH₂; Ti₂CoH₃; Zr₂Co₃H₉; NbH₂; C₃N₅H₆</td>
<td>Hydrogen storage, catalytic materials</td>
</tr>
<tr>
<td>Oxides</td>
<td>YBa₂Cu₃O₇-x; Bi₂VO₃; LaSrCrO₃; Na₂Mo₅Bi₁₅Ti₂O₂₅; BaBi₂Ni₂O₉</td>
<td>High-temperature superconductors, gas sensors, fuel cells</td>
</tr>
<tr>
<td>Chalcogenides</td>
<td>Phosphides of Mg, Ti, Zr, Mo, W; GaAs; Phosphides of Al, Ga, and In</td>
<td>High-temperature lubricants, semiconductors</td>
</tr>
</tbody>
</table>

![16 Chemical Engineering Education](image)
necessary, especially for the production of low-porosity or poreless materials. The final step in sample preparation determines the type of product synthesized; a powder product results from uncompacted powder reactants, while sintered products from cold-pressed compacts. Pressing the green mixture into special molds or machining pressed initial compacts yields complex-shaped articles.

The main production technologies of combustion synthesis are presented in the second block of Figure 2. They may be classified into several major types: powder production and sintering, and densification, by techniques including hydraulic, isostatic, or shock-wave pressing, extrusion, and hot-rolling. For highly exothermic reactions, where the products are in molten state, centrifugal casting is used to produce, for example, ceramic-lined pipes.

The third main step of CS technologies is post-synthesis treatment. Powder milling and sieving are used to yield powders with a desired particle size distribution. The synthesized materials and articles may also be machined into specified shapes and surface finish. Examples of combustion-synthesized articles, including ceramic engine parts, electric heating elements, high-temperature dielectrics, and cutting tools, are shown in Figure 3.

Owing to the characteristic features of CS, including high temperatures and short reaction times, unique materials can be made that cannot be synthesized by alternative techniques. Thus, CS combined with pressing has been used to obtain ceramic and intermetallic matrix-diamond composites with up to 20 wt% synthetic diamond, for advanced cutting tools. The graphitization during high-temperature treatment of diamond makes it impossible to produce such composites using conventional furnace techniques, while in the rapid combustion wave, diamond particles retain their shape, surface quality, and mechanical properties. The characteristic microstructure of the diamond-containing portion of a NiAl/diamond composite synthesized by CS is shown in Figure 4a (next page).

Another unique example is synthesis of silicon nitride whiskers with aspect ratio (ratio of length to diameter) of more than $10^4$ and length up to several centimeters (see Figure 4b). Such whiskers are widely used to reinforce different types of brittle ceramics to enhance their mechanical properties.

Finally, CS has been applied successfully in the production of so-called functionally graded materials (FGM). The concept of FGMs is to tailor nonuniform spatial distribution of components and phases in materi-

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**Figure 2. The main steps of combustion synthesis.**

<table>
<thead>
<tr>
<th>Green Mixture Preparation</th>
<th>Synthesis Technologies</th>
<th>Post - Synthesis Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying of reactant powders</td>
<td>Synthesis of powders and sintering</td>
<td>Ball milling</td>
</tr>
<tr>
<td>Weighing</td>
<td>Densification</td>
<td>Casting and coating</td>
</tr>
<tr>
<td>Mixing</td>
<td>Casting and coating</td>
<td>Polishing</td>
</tr>
<tr>
<td>Cold pressing of the pellet</td>
<td>Casting and coating</td>
<td>Final product</td>
</tr>
</tbody>
</table>

**Figure 3. Examples of articles produced by combustion synthesis (photograph courtesy of Academician Alexander G. Merzhanov, Chernogolovka, Russia).**
als, and hence combine mechanical, thermal, electrical, chemical, and other properties that cannot be realized in uniform materials. For example, the material structure may have a smooth transition from a metal phase with good mechanical strength on one side to a ceramic phase with thermal resistance on the other side (see Figure 5a). With a gradual variation in composition, FGMs do not have intermaterial boundaries found in multilayer materials, and hence they exhibit better resistance to thermal stress."\(^{[10]}\) The microstructure of a Cr\(_3\)C\(_2\)/Ni FGM, consolidated from a green compact consisting of powder layers with different Cr-C-Ni compositions by the CS+hot pressing method\(^{[11]}\) is shown in Figure 5b.

**Figure 4.** Examples of unique materials produced by combustion synthesis: (a) NiAl matrix/diamond composite, (b) silicon nitride whiskers.

**Figure 5.** Functionally graded materials (FGMs): (a) the concept of FGM; (b) Cr\(_3\)C\(_2\)/Ni FGM

**Figure 6.** Characteristic structure of the reaction wave during combustion synthesis.
MECHANISMS OF COMBUSTION SYNTHESIS

The features of high heating rates, high temperatures, and short times of reaction completion discussed above, although attractive for the synthesis of unique compounds, also make it difficult to study the mechanism of reaction wave propagation, which is essential in order to form materials with tailored microstructures and properties. Based on the results obtained in CS, a new field of fundamental research that incorporates concepts and principles from various branches of science and engineering, which investigates initial stages of chemical reactions in the combustion front and materials structure formation in the heterogeneous medium after passage of the front, is being developed.

In general, characteristics of the combustion wave are determined by the processes occurring in the heating, reaction, and post-combustion zones (see Figure 6). The length of the preheating zone varies from 0.05 to 0.3 mm, while the total wave is generally 1 to 2 mm and may be as wide as 20 to 30 mm for multistage reactions. A variety of physicochemical processes occur in different portions of the CS wave. The initial stage of structure formation is concurrent with the chemical reaction, where the driving force of the process is a reduction of Gibbs free energy resulting from formation of new chemical bonds under non-equilibrium conditions. In the final structure-formation process, physical effects are predominant where the free energy reduces further due to interfacial surface reduction, ordering of the crystal structure, and other related processes that occur without changes in the chemical composition under quasi-equilibrium conditions.

To study the variety of structural transformation processes, it is necessary to use a wide range of methods. For example, the evolution and morphological features of the structure during CS can be identified using a layer-by-layer microscopic and composition analysis of quenched samples. The dynamics of phase composition and crystal structure ordering can be monitored continuously by time-resolved X-ray diffraction (TRXRD). Also, microstructural analysis of the combustion front, using a digital high-speed microscopic video recording (DHSMVR) provides important information about the local conditions, which affect the synthesis process.

An illustration of the quenching technique involves comparison of the dynamics of structure formation in terrestrial and microgravity conditions. It has been shown that the microstructure of CS products is finer and more uniform in microgravity. For example, the growth rate of TiB₂ grains in molten Ni₃Al matrix during CS was four times smaller in microgravity (10⁻⁵g) as compared to normal (1g) conditions, thus yielding a final cermet product with finer grains that provide superior mechanical properties.

The application of the TRXRD method, which allows one to obtain X-ray patterns of several non-overlapping lines of each phase in complex systems every 0.1 seconds of observation, can be demonstrated on the combustion of titanium in air. In this system, a complicated mechanism was observed involving four intermediate phases that preceded the formation of the final equilibrium TiO₂ product:

\[
\alpha Ti \rightarrow TiN_x \rightarrow Ti_3O_5 - xN_x \rightarrow TiO_2 - xN_x \rightarrow TiO_2 (high \ T \ phase) \rightarrow TiO_2 (rutile \ structure)
\]

The kinetics of the appearance and disappearance of each phase are shown in Figure 8.

Finally, by using the DHSMVR method of in-situ observation of rapid processes, with a rate of recording up to 12,000 frames/second occurring at the microscopic level (spatial resolution of approximately 1.5 microns), significantly new information...
Figure 9. Microstructures of reaction wave during combustion synthesis: (a) quasihomogeneous reaction wave; (b) scintillating reaction wave.
about the microstructure of gasless heterogeneous combustion waves was recently obtained. It was shown[12] that while on the macroscopic length and time scales, the reaction appears to move in a steady mode, on the microscopic level it may have a complex unsteady character that is related to the reaction mechanism. In general, we may classify these waves into two types, according to their microstructures: quasihomogeneous reaction waves and scintillating reaction waves. In the former case, the wave moves steadily and there is relatively little variation of temperature along the surface of the front (see Figure 9a). In the latter case, however, a hot-spot initiates the reaction ahead of the front and the wave moves forward only as a consequence of the appearance of the hot-spots (see Figure 9b). Thus, an essential temperature nonuniformity exists in the reaction front that leads to nonuniformity of the product microstructure formation. In this case, the extent of nonuniformity can be controlled, i.e., the number and frequency of scintillations decrease by using finer reactant powders or samples with higher initial density.[14]

**THE CHALLENGES AHEAD**

There are some successful commercial applications of the combustion-synthesis technique for production of advanced materials. They include nitride ceramics, high-temperature heating elements, shape-memory alloys, ceramic-lined pipes, and high-performance composites. In my own laboratory at Notre Dame, we are currently working on two major applications with industrial partners. The first involves enhancement of cobalt-based alloys, where we are working with Zimmer, Inc., a world leader in production of orthopedic implants, to develop stronger alloys as well as new CS-based technology that will eliminate several manufacturing steps. The second project relates to improving production of emergency oxygen by combustion of low-exothermic condensed reactants, where we are collaborating with B/E Aerospace, Inc., the leading manufacturer of chemical oxygen generators for passenger aircraft applications.

While combustion synthesis offers a number of potential advantages over conventional techniques, some hurdles need to be overcome before it can enjoy widespread use. The foremost among these is a mechanistic understanding of reaction and structure-formation processes, which are indeed complex owing to the heterogeneous nature of the reaction media. This understanding is critical in order to produce materials with tailored microstructures and properties. As discussed above, excellent analytical tools are now becoming available that facilitate this understanding. Based on such insights, combustion synthesis is expected to become an important technique in the 21st century for the production of a variety of advanced materials.

**ACKNOWLEDGMENTS**

It is a pleasure to thank my long-term collaborators, Drs. Alexander Mukasyan and Alexander Rogachev, for their help in preparing this manuscript. I am grateful to the National Science Foundation (grant CTS-9900357) and the National Aeronautics and Space Administration (grant NAG3-2213) for support of my research in this field.

**REFERENCES**


USE OF THE RESIDUE THEOREM TO INVERT LAPLACE TRANSFORMS

N.W. LONEY
New Jersey Institute of Technology • Newark, NJ 07102

Chemical engineers are quite familiar with the use of the Laplace transform method for solving linear ordinary differential equations. Usually, the differential equation is converted to an equivalent algebraic equation, then the appropriate initial conditions are applied, and the resulting algebraic equation is prepared for inversion in order to recover the sought-after solution.

Frequently, the techniques to invert the resulting algebraic equation involve the use of a table of Laplace transforms. Most practitioners of this approach develop devices to extend their table of Laplace transforms when their particular inversion is not listed.

There is an alternate technique, however, that is especially useful when a difficult inversion is to be performed. This method employs a concept that is fundamental in the theory of functions of a complex variable—namely the residue theorem.

Following Mickley, Sherwood, and Reed, Churchill and Brown, and Detlland, the variables in

\[ F(s) = \int_0^\infty e^{-st}f(t)\,dt \]  

can be interpreted as a complex number. Here, \( F(s) \) is the Laplace transform of \( f(t) \). Further, except for singularities, \( F(s) \) is usually analytic (has a Taylor series expansion).

A frequently encountered class of problems in chemical engineering are the Sturm-Liouville problems, and it is useful to know that the transform of a solution to a Sturm-Liouville equation is analytic for all finite \( s \) except at the singularities (poles) of the system.

When \( F(s) \) is analytic, except for poles, the inverse transform is given by

\[ f(t) = \mathcal{L}^{-1}\{F(s)\} = \sum_{n=0}^{\infty} \rho_n(t) \]  

where \( \rho_n(t) \) is the residue of \( F(s) \) at the pole \( s_n \). Even though this concept is firmly grounded in the theory of functions of a complex variable, direct use of complex variables is not always required. A procedure is given below that avoids the direct use of complex variables.

PROCEDURE

Rewrite \( F(s) \) as a quotient

\[ F(s) = \frac{P(s)}{Q(s)} \]  

which enables us to quickly identify the singular points (poles) of \( F(s) \) and to determine if the degree of \( Q(s) \) is at least one greater than that of \( P(s) \). This procedure may require power series expansions of both \( P(s) \) and \( Q(s) \). If the degree of the denominator is at least one greater than that of the numerator, and the poles are simple (singularities of order one), then

\[ \rho_n(t) = \frac{\text{P}(s_n)}{\text{Q}'(s_n)} e^{s_n t} \]  

where \( \text{Q}'(s_n) \) is the derivative of \( Q(s) \) evaluated at the simple pole \( s_n \).
If the poles are of order m (multiple pole), then
\[ p_n(t) = e^{st} \sum_{j=1}^{m} A_j \frac{t^{j-1}}{(m-1)!} \]

The A’s are defined by
\[ A_j = \frac{1}{(m-1)!} \frac{d^{m-j}}{ds^{m-j}} \left( (s-s_n)^m F(s) \right) \]

Three examples are presented below. Examples 1 and 2 are elementary problems that can be quickly inverted by use of tables; they are presented here to illustrate the concept of the residue method. The third example demonstrates a more appropriate application of the method.

**EXAMPLE PROBLEMS**

1. **Simple Poles**

Suppose we need to invert
\[ F(s) = \frac{5s^2 - 7s + 17}{(s-1)(s^2 + 4)} = \frac{P(s)}{Q(s)} \]

Here,
\[ P(s) = 5s^2 - 7s + 17, \quad Q(s) = (s-1)(s^2 + 4), \quad Q'(s) = s^2 + 4 + (s-1)2s \]

The roots of Q(s) are the simple poles of F(s). Therefore, Eq. (4) is the appropriate form with which to evaluate the residues since the poles are not repeated; that is

\[ p_1(t) = \frac{P(1)}{Q'(1)} e^{-it} \]
\[ p_2(t) = \frac{P(2i)}{Q'(2i)} e^{-2it} \]
\[ p_{-2}(t) = \frac{P(-2i)}{Q'(-2i)} e^{2it} \]

so that use of Eq. (2) results in
\[ f(t) = p_1(t) + p_2(t) + p_{-2}(t) \]

That is
\[ f(t) = 3e^t + 2\cos 2t - \frac{5}{2} \sin 2t \]

2. **Multiple Poles**

Suppose we wish to invert
\[ F(s) = \frac{s}{(s^2 + 1)^2} \]

for which
\[ P(s) = s \quad \text{and} \quad Q(s) = (s^2 + 1)^2 \]

Q(s) has repeated roots at \( \pm i, \pm i \), so that the multiplicity, m, of each root is two. Therefore, as singularities of F(s), these are poles of order 2. Then using Eq. (5) with \( s = -i \),
\[ p_{-i}(t) = e^{-it} (A_1 + tA_2) \]

since \( m = 2 \). Also,
\[ \frac{(s+i)^2}{(s-i)^2} = \frac{s}{(s+i)^2} \]

Application of Eq. (6) gives
\[ A_1 = \frac{1}{(2-i)^2} \int \frac{s}{(s-i)^2} \frac{ds}{(s+i)^2} = \frac{1}{2} \left( \frac{1}{(s+i)^3} \right)_{s=-i} = 0 \]

and
\[ A_2 = \frac{1}{i!} \left( \frac{s}{(s-i)^2} \right)_{s=-i} = \frac{i}{4} \]

Therefore

\[ p_{-i}(t) = \frac{ti}{4} e^{-it} \]

Similarly

\[ p_i(t) = -\frac{ti}{4} e^{it} \]

such that Eq. (2) results in
\[ f(t) = p_{-i}(t) + p_i(t) = \frac{1}{2} \left( \frac{e^{it} - e^{-it}}{2i} \right) = \frac{1}{2} \sin t \]

in which use of the identities
\[ \cos \theta = \frac{e^{i\theta} + e^{-i\theta}}{2} \quad \text{and} \quad \sin \theta = \frac{e^{i\theta} - e^{-i\theta}}{2i} \]

are employed to express the final results of both examples.

3. **Diffusivities of Gases in Polymers**

Consider a model of diffusion through a membrane that separates two compartments of a continuous-flow permeation chamber. Then, following Felder, Spence, and Ferrell, such at time \( t=0 \), a penetrant is introduced into one compartment (the upstream compartment) and permeates through the membrane into a stream flowing through the other (downstream) compartment. Further, this model includes the following assumptions:

- **Diffusion of the penetrant in the gas phase and absorption at the membrane surface are instantaneous processes.**
- **Diffusion in the membrane is Fickian with a constant diffusivity.**
- **The concentration of dissolved gas at the downstream surface of the membrane is always sufficiently low compared to that at the upstream surface, such that the downstream surface concentration may be set equal to zero.**

Then, diffusion through a flat membrane of thickness \( h \) is described by
\[ \frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2} \]

subject to
Application of Eq. (1) to transform Eqs. (24 - 27) results in the second-order constant-coefficient homogeneous differential equation

\[ 0 = d^2 y(s,x) \over ds^2 - sy \over D \]  

subject to

\[ y(s,0) = C_1 \over s \]  

and

\[ y(s,h) = 0 \]  

The solution to the boundary-value problem described by Eqs. (28-30) is

\[ y(s,x) = C_1 \left[ \frac{\sinh \left( \frac{s}{D} h \right) \cosh \left( \frac{s}{D} x \right) - \cosh \left( \frac{s}{D} h \right) \sinh \left( \frac{s}{D} x \right)}{s \sinh \left( \frac{s}{D} h \right)} \right] \]  

Then, applying Eqs. (2-4) to invert \( y(s,x) \), we get

\[ L^{-1}[y(s,x)] = C(t,x) = C_1 \sum_{n=0}^{\infty} \frac{P(s_n,x)}{Q'(s_n)} \exp(s_n t) = \]  

\[ C_1 L^{-1} \left[ \frac{\sinh(h-x) \over s \over D}{s \sinh \left( \frac{s}{D} h \right)} \right] \]  

Recall that

\[ \frac{P(s_n)}{Q'(s_n)} = \lim_{s \to s_n} \frac{P(s)}{Q(s)-Q(s_n)} = \lim_{s \to s_n} (s-s_n) \frac{P(s)}{Q(s)} \]  

such that for \( s_n = 0 \)

\[ \rho_0(t) = \lim_{s \to 0} \frac{P(s)}{Q'(0)} = \lim_{s \to 0} \frac{P(s)}{Q(s)} \]  

Then for

\[ y(s,x) = \frac{P(s,x)}{Q(s)} \]  

where

\[ P(s,x) = \sinh(h-x) \over s \over D \]  

and

\[ Q(s) = s \sinh \left( \frac{s}{D} h \right) \]  

The simplifying substitution \( i\lambda = \sqrt{s/D} \) results in

\[ \lambda = n \pi \over h \quad n = 1,2,\ldots \]  

That is, when Eq. (37) is set equal to zero, either \( s = 0 \) or \( \sinh ii\lambda = 0 \). The case \( s = 0 \) results in the residue \( \rho_0(t) \) given above (Eq. 38), while the case \( s \neq 0 \) gives \( \sinh ii\lambda = 0 \), a condition that is satisfied for the values of \( \lambda \) as given in Eq. (40). Finally, after performing the necessary algebra, we get the result

\[ \rho_n(t,x) = \frac{P(s_n,x)}{Q'(s_n)} e^{sn t} = \frac{2}{n\pi} \sin \left( \frac{n\pi x}{h} \right) e^{-n^2 t} \]  

and the concentration profile is

\[ C(t,x) = C_1 \left[ \frac{-h-x}{h} - \frac{2}{n\pi} \sum_{n=1}^{\infty} \frac{n^2 \pi^2 h^2}{D} \sin \left( \frac{n\pi x}{h} \right) \right] \]  

Then, the rate of penetrant across the surface \( x = h \) is given by

\[ J(t) = -DA \frac{\partial C}{\partial x} \bigg|_{x=h} = \frac{DAC_C}{h} \left[ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left( \frac{n^2 \pi^2 h^2}{D} \right) \right] \]  

for a flat membrane with a surface area \( A \). Also notice that the steady-state rate, \( J_{ss} \), is given by

\[ J_{ss} = D \frac{AC_C}{h} \]  

For an example involving cylindrical geometry, the reader is directed to the recent literature where a model based on membrane separation is treated by Ramraj, Farrell, and Loney. Also, a model involving membrane separation with chemical reaction in a flowing system is treated by Loney. Inversion by the residue method is not a new concept; however, it can be very useful in efficiently solving systems of non-homogeneous linear partial differential equations.

REFERENCES

Random Thoughts . . .

TRUTH IN ADVERTISING

RICHARD M. FELDER
North Carolina State University • Raleigh NC 27695

Most of us in this business are periodically called on to evaluate award nominations and applications for faculty positions. It's not an easy job if you take it seriously. You have to make intelligent judgments about somebody's qualifications based on lists of articles in journals you never heard of on subjects you're unfamiliar with written by multiple authors whose roles in the work are undefined. You also have to deal with collections of reference letters unanimously assuring you that the applicant is currently or potentially the finest researcher, teacher, and all-around human being the world has ever known. Interpreting all that unfiltered verbiage to figure out just how good someone actually is takes considerable experience and skill.

As a service to the profession, I've prepared a glossary of classifications that will make interpretation of award and application dossier s a snap once everyone agrees to adopt it. Here, for example, is how a hypothetical citation might appear in a dossier submitted by one Alvin Tsimmes, followed by the glossary.

23. B.A. Mensch, A. Tsimmes, and O.Y. Gevalt

Categories of authors:
(a) did most of the research;
(b) contributed significantly to the research;
(c) occasionally attended meetings and had a vague idea what the research was about;
(d) clueless about the research but part of a faculty group that automatically shared authorship of all papers on the subject;
(e) owned some equipment needed for the research;
(f) had nothing to do with the research but famous enough to guarantee the paper's acceptance;
(g) department head

Categories of papers:
(h) classic in its field—hundreds of citations;
(i) many citations by non-authors;
(j) mainly or entirely self-citations;
(k) no citations;
(l) named in a reader's poll as the paper least likely to be cited by anyone ever

Categories of journals:
(m) top of the line: non-National Academy members can forget it;
(n) prestigious and hard to get into: referees are those people whose hobby is asking sarcastic questions at conferences to prove they know more than the presenters;
(o) refereed;
(p) sort of refereed: condition for acceptance is lack of obvious gross errors;
(q) non-refereed: condition for acceptance is submission;
(r) last resort: authors who submit papers get a free lifetime subscription, two large pizzas with toppings of their choice, and a shoeshine;
(s) accepts papers rejected by (r)

Next, here is the list of authors of Tsimmes's reference letters:
1. Dr. R.U. Sirius;
2. Mr. I.C. Dimmly;
3. Prof. U.R. Toest

Categories of reference letters:
(t) completely sincere;
(u) exaggerated but more or less accurate;
(v) politely camouflaged negative opinion;
(w) form letter—respondent never heard of the applicant and didn't look at the dossier;
(x) blatant lying

The creativity required to write good Category (v) letters has led to such gems as

1. "I cannot recommend him too highly,"
2. "With her on your staff, there's no telling what you might accomplish,"
3. "I am pleased to say that this candidate is a former colleague of mine,"
4. "I can assure you that no person would be better for this job,"
5. "I would waste no time in making this candidate an offer of employment,"

and the ever-popular
1. "I've known Mr. Jones for many years, and you'll be lucky if you get him to work for you!"

Dossier evaluators could get a serious headache trying to interpret these remarks and possibly make a serious mistake if they guess wrong, but a "v" by the authors' names would make life easy for everyone (except perhaps Mr. Jones).

Okay, now that we've got all that worked out, let's discuss applying the same technique to TV commercials, political speeches, marriage proposals, and perhaps even journal columns.

This column is a facetious and excessively cynical adaptation of a clever idea suggested by Kay C. Dee of Tulane in a casual conversation. The author should be ashamed of himself.

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ANALYSIS AND SIMULATION OF A SOLAR-POWERED REFRIGERATION CYCLE

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

Rapidly escalating gasoline and heating oil costs in the Spring of 2000 represented the first major energy consumption crisis in this country since 1973. Nonetheless, this experience served once again to demonstrate the vulnerability of the nations of the Western world to production and marketing policies in the various oil-producing nations. One of the many energy conservation efforts in the 1970s after that earlier crisis was associated with a search for alternative methods of cooling, air-conditioning, and refrigeration. One of these methods, using low-grade thermal energy (e.g., solar or waste heat) to power the cooling cycle, forms the subject of this article.

The most expensive step, corresponding to the greatest amount of energy consumption, in conventional refrigeration cycles is the mechanical compression step, wherein a refrigerant vapor is compressed from a low pressure to a higher pressure. It is then condensed to liquid form in, typically, an air-cooled heat exchanger before expansion back to the same low pressure in an expansion valve, followed by vaporization—whereby the refrigeration effect occurs. This refrigerant vapor is then recompressed to the higher pressure, and the cycle is complete. These mechanical compressors are typically driven by electric motors or internal combustion engines, the energy sources for which can generally be traced back to fossil fuels or nuclear power.

For more than twenty years now, the widespread use of vapor-compression refrigeration for commercial and household air conditioning has caused a shift in the seasonal peak for electric power production from mid-winter to mid-summer. This trend naturally suggests the possibility of matching demand with availability, i.e., the use of solar thermal energy in the neighborhood of 200°F to power the cooling cycle rather than mechanical work, at least in certain climes. Related to this possibility is the suggestion of heat-driven mobile refrigeration cycles, as in an automobile, wherein waste heat from engine cooling water could serve as the driving medium. All of these developments were naturally spurred by various energy tax credits, also inaugurated in the 1970s.

PROCESS DESCRIPTION

By contrast with the conventional vapor-compression refrigeration cycle with its two refrigerant pressure levels, in this solar-powered refrigeration cycle there are three different pressure levels: low, medium, and high. Here, the high-pressure is achieved by pumping a portion of the liquid refrigerant stream, and not a vapor stream. This high-pressure liquid refrigerant stream is vaporized in a solar-collector heat exchanger. The high-pressure vaporized stream then serves as the motive stream to a thermal (or jet) compressor, wherein this stream sucks up the low-pressure stream from the refrigeration coil, thereby creating a medium-pressure stream (much like a laboratory aspirator). This latter stream is then totally condensed, as in a conventional refrigeration cycle, typically by heat exchange with ambient air. Part of this condensed steam feeds through an expansion valve in the low-pressure loop and then evaporates in the refrigeration coil, again just as in conventional refrigeration. The remainder of the condensed mixed stream is pumped in the high-pressure loop and to the solar collector, thus completing the refrigeration cycle.

It is clear that the crucial piece of equipment in the above cycle is the thermal compressor. With its lack of moving parts, it is certainly an attractive alternative to the conventional mechanical compressor. Rigorous mathematical modeling of thermal compressors is a rather formidable task,
however. Earlier one-dimensional models of such devices proceeded from first principles in fluid mechanics and thermodynamics. The model of DeFrates and Hoer[6] was later coded in a FORTRAN routine, suitable for incorporation into the early FLOWTRAN[8] system for CAPD (but never implemented therein). Indeed, most of today’s state-of-the-art CAPD systems in chemical engineering still do not have building blocks or modules for thermal compressors. This lack is due to, among other things, the complexity of the models themselves, difficulties in generalization, and the need for detailed specifications.

There was an early attempt at modeling a solar-powered refrigeration cycle using the seminal FLOWTRAN system.[9] The module used for the thermal compressor was an adiabatic flash block, in which the high-pressure stream was simply mixed adiabatically with the low-pressure stream to yield the medium-pressure stream. The same effect could similarly have been achieved with a mixer module also operating in adiabatic fashion. Thus, these modules in the FLOWTRAN system would allow a pressure rise across them, with no concern as to how this pressure increase was to be achieved. The same, admittedly unrealistic, capability existed in the PRO/II® system.[10]

HYSYS® SIMULATION

Current CAPD systems in chemical engineering have a graphical user interface (GUI) as their input/output medium, and operate on a personal computer (PC) platform. One such modern system is HYSYS—the precursor of which was HYSIM,[11] both of which were developed by Hyprotech, Ltd., in Canada. This HYSYS system is the one presently used in the chemical engineering instructional program at Georgia Tech, and thus it is the one employed in this study.

The process flow diagram (PFD) for the solar-powered refrigeration cycle, as constructed by the HYSYS system, is shown in Figure 1. The various streams and unit operations in this PFD, as well as their functions, are described in Table 1. This HYSYS system is more realistic in the sense that it will not allow a pressure rise across either an adiabatic flashing or mixing operation. That is, the outlet stream pressure from the unit cannot exceed the pressure of any one of the incoming process streams. And, as with most present CAPD systems in chemical engineering, there is no formal thermal compressor module in the HYSYS system. Thus, an alternative method must be developed to simulate this device in the refrigeration cycle, the description of which follows.

A logical place to begin the description of this three-pressure-level refrigeration cycle is with the mixed vapor stream exiting the MIXER unit. This stream is at the medium pressure of the loop and feeds the air-cooled condenser (duty of QCOND), as in a conventional air conditioning cycle. It was assumed here that the exiting stream from this condenser was saturated liquid refrigerant at 125°F. This as-

![Figure 1. HYSYS process flow diagram for a solar-powered refrigeration cycle.](image)

### TABLE 1

<table>
<thead>
<tr>
<th>Unit Operation Name</th>
<th>Operation Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIXER</td>
<td>Mixes the vapor streams (both at the same medium pressure) from the high-pressure (FROMCMPRES) and the low-pressure (FROMEXPAND) loops</td>
</tr>
<tr>
<td>CONDENSER</td>
<td>Rejects heat from the mixed vapor stream (TOCOND) to the ambient air (duty = QCOND)</td>
</tr>
<tr>
<td>SPLITTER</td>
<td>Splits the condensed stream (TOSPLIT) into the two parts feeding the low-pressure (TOVALVE) and high-pressure (TOPUMP) loops</td>
</tr>
<tr>
<td>EXPANSION</td>
<td>Reduces the pressure of the liquid stream in the low-pressure loop (TOCOIL)</td>
</tr>
<tr>
<td>REFRIGCOIL</td>
<td>Extracts heat from the environment to vaporize the stream in the low-pressure loop (FROMCOIL)</td>
</tr>
<tr>
<td>REFRIGDUTY</td>
<td>Varies the refrigerant flow rate in the low-pressure loop to achieve the desired refrigeration duty in the coil (QCOIL)</td>
</tr>
<tr>
<td>COMPRESSOR</td>
<td>Compresses (work = WCOMP) the low-pressure vapor stream to the cycle’s medium pressure (FROMCMPRESS)</td>
</tr>
<tr>
<td>PUMP</td>
<td>Increases the pressure of the liquid stream (TOPUMP) in the high-pressure loop (work = WPUMP)</td>
</tr>
<tr>
<td>COLLECTOR</td>
<td>Vaporizes the liquid stream (FROMPUMP) in the high-pressure loop with solar or waste heat (duty = QSOLAR)</td>
</tr>
<tr>
<td>EXPANDER</td>
<td>Reduces the pressure (work = WEXPAND) of the vapor stream in the high-pressure loop (TOEXPAND) to the cycle’s medium pressure (FROMEXPAND)</td>
</tr>
<tr>
<td>EQUALWORKS</td>
<td>Equates the work of compression (WCOMP) in the COMPRESSOR with the work of expansion (WEXPAND) in the EXPANDER</td>
</tr>
</tbody>
</table>
umption thus determined the medium-pressure level in this process for a given (pure component) refrigerant. A summary of the various assumed operating conditions for all of these simulations is given in Table 2.

The liquid stream exiting the condenser is fed to a tee module (named SPLITTER); here, the stream is divided into the two parts, feeding the low-pressure and high-pressure loops, respectively. The stream for the low-pressure loop is fed through a conventional expansion valve and then to the refrigeration coil. The duty (Q_COIL) of this coil (and hence of the refrigeration cycle) was set at 4 tons = 48,000 BTU/hr = 0.48 therm/hr in all of these simulations. This duty is a typical value for a modern residential dwelling of moderate size. This condition was achieved with the aid of an adjust module (named REFRIGDUTY), which varied the flow rate of refrigerant in the low-pressure or cold loop, much like a proportional controller. The thermodynamic condition of the refrigerant leaving the coil was assumed to be saturated vapor at 40°F; this condition then specified the operating pressure level in the cold loop. The refrigerant vapor was next supplied to a conventional mechanical compressor module (nonexistent in the actual process itself, of course), which recompressed this stream to the medium pressure of the process before entering the mixer module. The power requirement of this compressor is denoted as W_COMP.

Returning to the tee module (SPLITTER) following the air condenser, the remainder of the saturated liquid refrigerant was pumped (power requirement = WPUMP) to the high-pressure level of the process. This latter value, for a given refrigerant, was dictated by the condition that the refrigerant exiting the downstream solar collector (duty of Q_SOLAR) was saturated vapor at 200°F—a not unreasonable value for modern solar collection systems. This collector, as well as the air condenser and the refrigeration coil, were all modeled by simple process-utility heat exchangers in these simulations. Also, for simplicity, any process fluid pressure drops in these exchangers were neglected.

Lastly, the saturated refrigerant vapor from the solar collector is fed to a conventional mechanical expander (again, nonexistent in the actual process). This expander module reduces the vapor refrigerant pressure down to the medium-pressure level in the process and generates a work stream denoted as W_EXPAND. Another adjust module (named EQUALWORKS) equates the power required by the mechanical compressor with that generated by the expander, by varying the refrigerant flow rate in the high-pressure loop. The process output stream from this expander, at the same medium-pressure level as the vapor stream from the compressor is then mixed with this latter stream to form the input to the air condenser, thus closing the loops.

That part of the process flow diagram in Figure 1 representing the thermal compressor is enclosed within the dashed-line envelope of that figure. The units enclosed therein include the mechanical compressor, mixer, expander, and the adjust block to equate the work streams for the two mechanical units. Also, for comparison purposes, the HYSYS process flow diagram for a comparable and conventional vapor-compression refrigeration cycle is shown in Figure 2. It is obviously considerably simpler, in that the high-pressure loop from Figure 1 is no longer present and there is no need to construct an artificial representation of a thermal compression unit here.

Four different pure-component refrigerants were investigated in this simulation study. These are summarized in Table 3. The first one of these, R-113, has been a popular

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Low Pressure (P_L, psia)</th>
<th>Medium Pressure (P_M, psia)</th>
<th>High Pressure (P_H, psia)</th>
<th>Cold Loop Flow Rate (M, lbs/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-113</td>
<td>2.906</td>
<td>17.34</td>
<td>55.03</td>
<td>1014</td>
</tr>
<tr>
<td>R-134a</td>
<td>49.7</td>
<td>200</td>
<td>506.1</td>
<td>881</td>
</tr>
<tr>
<td>Propane</td>
<td>78.49</td>
<td>258.8</td>
<td>581.8</td>
<td>477</td>
</tr>
<tr>
<td>Iso-propanol (IPA)</td>
<td>0.25</td>
<td>3.96</td>
<td>22.12</td>
<td>179.5</td>
</tr>
</tbody>
</table>
refrigerant for many home air conditioning systems and was the refrigerant employed in earlier analyses of refrigeration cycles using a jet ejector. This particular refrigerant is rapidly being replaced, however, with R-134a—a more environmentally friendly species. The remaining two prospective refrigerants considered (propane and isopropanol) were similarly studied by earlier investigators of these cycles. Once a refrigerant had been chosen and given the operating conditions specified in Table 2, all of the remaining process conditions followed. These latter conditions, such as the three operating pressures in the cycle and the refrigerant flow rate in the cold or low-pressure loop, are also given in Table 3. Lastly, the Peng-Robinson thermodynamic system for computing physical properties as implemented in the HYSYS system was employed throughout this work.

SIMULATION RESULTS

The use of each of the above four refrigerants in a solar-powered air conditioning cycle rated at 4 tons of refrigeration was investigated. Specifically, the effect of the adiabatic efficiencies of the compressor/expander combination on the performance of the cycle was determined. Five different values of this efficiency were chosen: 100, 90, 75, 60, and 50%. The same value of the efficiency (e.g., 75%) was applied to both the compressor and the expander in a given simulation. These efficiency values bracket the compression ratio efficiencies determined experimentally (56 to 74%) in an earlier study of jet ejectors using butane and hexane as the process fluids.

The simulation results obtained for the four refrigerants are summarized in Tables 4-7, respectively. Some general observations from these tables may be made first. Thus, all of the dependent parameters shown in the tables, save for the coefficient of performance (COP), increase monotonically with decreasing compressor/expander efficiency. For all practical purposes, the condenser duty (Qc) exceeds the solar collector duty (Qs) by the assumed refrigeration duty (Qr = 0.48 therm/hr). This is readily apparent from the specific curves in Figure 3 for the condenser and collector duties in the case of refrigerant R-134a. The small amount of thermal energy contributed by the pump work (Wp) is also rejected by the condenser. This latter power stream is the only mechanical energy contribution to this loop, and varies from fractions of a horsepower up to 4+ hp in the worst case of propane as the refrigerant at 50% adiabatic efficiencies (Table 6). The magnitude of the pump work stream is obviously directly related to the magnitude of the hot loop circulation rate (Mh in these tables).

The coefficient of performance (COP) for a refrigeration cycle or heat pump is generally computed as the ratio of the refrigeration duty or the amount of heat pumped to the thermal energy or mechanical work supplied to the cycle. Thus, a COP value in this study was computed as the quotient of the refrigeration effect (Qr) divided by the solar collector duty (Qs), or COP = Qr/Qs. Note that the small amount of mechanical work contributed to the cycle by the pump (Wp) was ignored. This COP quantity then varies in the range of 0.45-0.55 down to 0.1+ as the adiabatic efficiencies decrease. The best values are observed in the case of isopropanol (Table 7). Among other deficiencies, however, this refrigerant suffers from the rather large compression ratio (>10) required in the compression step (see Table 3). Isopropanol is followed in performance by R-113, as shown in Table 4. Propane and R-134a (Table 5) are virtually identical in displaying the poorest performance of the four refrigerants; they also require the highest operating pressures in the loops.

The COP values calculated above may be compared with maximum theoretical values. Thus, Chen also begins his analysis of this cycle by ignoring the negligible amount of work contributed to the cycle by the pump (Wp). The maximum attainable coefficient of performance for the ejector-operated refrigeration cycle is then equal to...
**TABLE 4**

Effects of Compressor/Expander Efficiencies with R-113
(Refrigeration Duty (QR) = 4 tons = 0.48 therm/hr)

<table>
<thead>
<tr>
<th>Compressor/Expander Efficiency (E), %</th>
<th>Collector Duty (Qc), therms/hr</th>
<th>Condenser Duty (Qr), therms/hr</th>
<th>COP (Qc/Qr)</th>
<th>Compressor/Expander Pump Work (W), hp</th>
<th>Pump Work (W), hp</th>
<th>Flow Rate (M), lbs/hr</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>0.982</td>
<td>1.463</td>
<td>0.489</td>
<td>3.881</td>
<td>0.053</td>
<td>1363</td>
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<td>90</td>
<td>1.212</td>
<td>1.694</td>
<td>0.396</td>
<td>4.312</td>
<td>0.066</td>
<td>1683</td>
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<tr>
<td>75</td>
<td>1.746</td>
<td>2.228</td>
<td>0.275</td>
<td>5.175</td>
<td>0.095</td>
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<tr>
<td>60</td>
<td>2.728</td>
<td>3.211</td>
<td>0.176</td>
<td>6.469</td>
<td>0.148</td>
<td>3787</td>
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<td>50</td>
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<td>4.413</td>
<td>0.122</td>
<td>7.762</td>
<td>0.213</td>
<td>5453</td>
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</tbody>
</table>

**TABLE 5**

Effects of Compressor/Expander Efficiencies with R-134a
(Refrigeration Duty (QR) = 4 tons = 0.48 therm/hr)

<table>
<thead>
<tr>
<th>Compressor/Expander Efficiency (E), %</th>
<th>Collector Duty (Qc), therms/hr</th>
<th>Condenser Duty (Qr), therms/hr</th>
<th>COP (Qc/Qr)</th>
<th>Compressor/Expander Pump Work (W), hp</th>
<th>Pump Work (W), hp</th>
<th>Flow Rate (M), lbs/hr</th>
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<tr>
<td>100</td>
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<td>0.893</td>
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<td>75</td>
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<td>60</td>
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<td>50</td>
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<td>8.677</td>
<td>2.894</td>
<td>6669</td>
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</tbody>
</table>

**TABLE 6**

Effects of Compressor/Expander Efficiencies with Propane
(Refrigeration Duty (QR) = 4 tons = 0.48 therm/hr)

<table>
<thead>
<tr>
<th>Compressor/Expander Efficiency (E), %</th>
<th>Collector Duty (Qc), therms/hr</th>
<th>Condenser Duty (Qr), therms/hr</th>
<th>COP (Qc/Qr)</th>
<th>Compressor/Expander Pump Work (W), hp</th>
<th>Pump Work (W), hp</th>
<th>Flow Rate (M), lbs/hr</th>
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<tr>
<td>100</td>
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<td>90</td>
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<td>75</td>
<td>1.913</td>
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<td>60</td>
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<tr>
<td>50</td>
<td>4.304</td>
<td>4.894</td>
<td>0.112</td>
<td>8.910</td>
<td>4.329</td>
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**TABLE 7**

Effects of Compressor/Expander Efficiencies with iso-Propanol
(Refrigeration Duty (QR) = 4 tons = 0.48 therm/hr)

<table>
<thead>
<tr>
<th>Compressor/Expander Efficiency (E), %</th>
<th>Collector Duty (Qc), therms/hr</th>
<th>Condenser Duty (Qr), therms/hr</th>
<th>COP (Qc/Qr)</th>
<th>Compressor/Expander Pump Work (W), hp</th>
<th>Pump Work (W), hp</th>
<th>Flow Rate (M), lbs/hr</th>
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</thead>
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<tr>
<td>100</td>
<td>0.884</td>
<td>1.364</td>
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<td>90</td>
<td>1.092</td>
<td>1.572</td>
<td>0.440</td>
<td>4.049</td>
<td>0.013</td>
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</tr>
<tr>
<td>75</td>
<td>1.572</td>
<td>2.052</td>
<td>0.305</td>
<td>4.859</td>
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<tr>
<td>60</td>
<td>2.456</td>
<td>2.937</td>
<td>0.195</td>
<td>6.073</td>
<td>0.029</td>
<td>753</td>
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<tr>
<td>50</td>
<td>3.537</td>
<td>4.018</td>
<td>0.136</td>
<td>7.288</td>
<td>0.041</td>
<td>1084</td>
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</tbody>
</table>

Figure 3. Air condenser and solar collector duties for a 4-ton solar-powered air-conditioning cycle, with R-134a as the refrigerant, as functions of the adiabatic efficiencies of the compressor and expander.

The selection of the heat rejection temperature (T₀) is clearly somewhat arbitrary. The selection of the condenser temperature (Tc) of 125°F as this rejection temperature is admittedly a very conservative choice, leading to the poorest or lowest values for the theoretical COP. As this temperature is reduced, the computed theoretical COP value improves, as summarized in Table 8, wherein these values are calculated for heat rejection temperatures of T₀ = 125, 110, 100, 90, and 77°F. The value of T₀ = 100°F, for example, was chosen by Chen in his analysis. Of course, a common value for this latter quantity is 77°F, particularly in thermodynamic availability or exergy analyses.

In his more thorough analysis of this cycle, Hammer computes various other theoretical coefficients of performance values, which are generally less than those from the Carnot analysis and thus somewhat more realistic. An analysis assuming an isentropic turbine-compressor combination with the coefficient of performance for a Carnot refrigeration cycle (COPc) working between the temperatures of the refrigeration coil (TR) and the heat rejection temperature (T₀), multiplied by the efficiency of a Carnot heat engine (Ee) operating between the solar collector temperature (T₅) and the rejection temperature of T₀. The above Carnot refrigeration cycle can also be viewed as a heat pump operating in the cooling mode between the two temperatures of TR and T₀. If one selects the condenser temperature (Tc) as the heat rejection temperature, then

\[ \text{COP}_c = \frac{T_R}{T_C - T_R} = \frac{500}{585 - 500} = 5.882 \] (1)

and

\[ E_e = \frac{T_S - T_C}{T_S} = \frac{660 - 585}{660} = 0.1136 \] (2)

from which \( \text{COP} = (\text{COP}_c)(E_e) = 0.6684 \). The best COP values (at adiabatic efficiency values = 100%) in Tables 4-7 are seen to approach this value.

The selection of the heat rejection temperature (T₀) is clearly somewhat arbitrary. The selection of the condenser temperature (Tc) of 125°F as this rejection temperature is admittedly a very conservative choice, leading to the poorest or lowest values for the theoretical COP. As this temperature is reduced, the computed theoretical COP value improves, as summarized in Table 8, wherein these values are calculated for heat rejection temperatures of T₀ = 125, 110, 100, 90, and 77°F. The value of T₀ = 100°F, for example, was chosen by Chen in his analysis. Of course, a common value for this latter quantity is 77°F, particularly in thermodynamic availability or exergy analyses.
no mixing losses yields COP values not much less than the Carnot values. Once mixing losses are allowed to affect the results, using either an ideal gas model or a real gas model, the COP values drop markedly due to the internal irreversibilities or lost work. Hamner also reports experimental data on such an ejector-operated refrigeration cycle, rated at approximately one ton of refrigeration and employing R-11 as the refrigerant. Experimental COP values of about 0.10 to 0.25 were obtained for pressure ratios \( \frac{P_s}{P_c} \) of 5.0 to 7.5.

**CONCLUSIONS**

This article has demonstrated the applicability of the HYSYS computer-aided process design system to the simulation and analysis of a solar-powered refrigeration cycle. While such a cycle consists of a number of standard chemical process equipment items such as heat exchangers, a pump, and an expansion valve, the key hardware element in this cycle is a thermal compressor or jet ejector. Models of the latter item, while a relatively common piece of processing equipment in the chemical and allied industries, are not that extant in computer-aided process design systems such as HYSYS or comparable software packages. The employment of an adjust or control module to balance the work of a compressor and an expander in a cycle was illustrated in this work.

The coefficient of performance (COP) values for refrigeration cycles driven by a solar collector and jet ejector are admittedly much smaller than those of conventional cycles employing mechanical compressors. As numerous authors\(^1\) have pointed out, however, applications of the former may be economical in cases wherein the required input heat is very inexpensive (e.g., solar energy) or it would be otherwise wasted, as from the cooling system of an automobile engine. And there are certainly more than just technological factors operative in this arena.\(^4\) Lastly, it should be remembered that the energy input to a mechanical vapor-compression refrigeration cycle generally originates from an electrical power plant. This power often derives from the combustion of a fuel with a process efficiency of about 33%. Thus, the ultimate amount of energy required in such a mechanical cycle is roughly three times the amount actually supplied to the compressor.

**TABLE 8**

Influence of Heat Rejection Temperature \( (T_R) \) on COP and Efficiency Values \( (T_s = 40°F, \ T_c = 200°F) \)

<table>
<thead>
<tr>
<th>Rejection Temperature ( (T_R) )</th>
<th>Refrigeration Cycle COP</th>
<th>Efficiency of heat engine ( (E_{h}) )</th>
<th>Overall cycle COP ( = \frac{\text{COP} \times E_h}{1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 5.882</td>
<td>0.1136</td>
<td>0.6684</td>
<td></td>
</tr>
<tr>
<td>110 7.143</td>
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<td>0.9740</td>
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</tr>
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<td>90 10.000</td>
<td>0.1667</td>
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</tr>
<tr>
<td>77 13.514</td>
<td>0.1864</td>
<td>2.5184</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE FROM OCTAVE LEVENSESPIL**

I have written a little book especially designed for the first engineering thermo course. It is called

[Understanding Engineering Thermo](mailto:octave@che.orst.edu)

and it uses a radically different teaching approach. Students like it.

The OSU Bookstore (Box 489, Corvallis OR 97339) is distributing it at $20 plus mailing cost. If you are a thermo teacher and want a desk copy, contact me at

Chemical Engineering Department
Gleeson 103
Oregon State University
Corvallis OR 97331

Octave Levenspiel
octave@che.orst.edu

Perhaps the major contribution of this work is of a pedagogical nature. Thus, this study of a solar-powered refrigeration cycle, exploring different refrigerants, efficiencies, operating conditions, etc., could represent an excellent computer-aided design project in an introductory engineering thermodynamics course. It is in this spirit that this study was formulated.

**REFERENCES**

THE EFFECT OF PUBLICATION RATE PROFILE ON CITATION STATISTICS

MORDECHAI SHACHAM  
Ben-Gurion University of the Negev • Beer-Sheva 84105, Israel  
NEIMA BRAUNER  
Tel-Aviv University • Tel-Aviv 69978, Israel

The application of citation statistics for evaluating and comparing research groups has continually increased in recent years. One reason for this trend is that such statistics are perceived to be quantitative and objective. In addition, the pertinent information is available through the Internet and the evaluation can be carried out with minimal expense.

Unfortunately, there are many pitfalls in using citation statistics as a sole measure of research achievements. Some of the pitfalls are mentioned, for example, by Grossman[1] and Angus, et al.[2] Those pitfalls can often lead to absurd results, as was recently shown in letters to the editor by Braun[3] and Reedijk.[4] The response from the institutes that provide the citation statistics and the citation analysts (Blazick,[5] van Raan[6]) state that citation analysis should be used only as an additional, supporting tool to peer review and should never be used in “isolation.”

In the 1995 NRC report,[7] results of a research-related comparison study of 93 chemical engineering departments awarding PhDs in the US were reported. In that study, qualitative measures of research achievements (such as peer review) and quantitative measures, both intensive (such as the number of citations per paper, CPP) and extensive (e.g., total number of publications and citations), were used. But even such an extensive and thorough study cannot be completely faultless (as was pointed out by Grossman[1] and Angus, et al.[2]) because of technical difficulties in collecting reliable citation data and the very different nature of the evaluated departments.

Furthermore, conducting both a thorough peer review and a quantitative evaluation can be time consuming and expensive. For this reason there is a growing tendency to rely on quantitative measures alone in evaluating and comparing research programs. Van Raan[6] has recently evaluated the validity of a measurement that he calls the “impact of the group.” This measure is essentially the CPP divided by the CPP world average of the field (WAF). Studying various departments in The Netherlands, van Raan has found a strong correlation between quantitative measures, such as the CPP/WAF and results of the peer reviews. In spite of these positive results, he does not recommend the use of quantitative measures alone and calls for carrying out further research in cases where considerable differences are detected between results obtained by employing different measures.

In this paper the influence of the publication profile on the CPP is investigated. In the next section an example is pre-
...there are...pitfalls in using citation statistics as a sole measure of research achievements [that] can often lead to absurd results....The response from the institutes that provide the citation statistics and the citation analysts state that citation analysis should be used only as an additional, supporting tool for peer review...
"slope: 0," "slope: +1," and "slope: +2") are similar, except that the number of papers published per year changes according to the specified slope.

The results of the simulation are summarized in the "Total" column of Table 1 and in Figures 1 to 4. Figure 1 shows the total number of publications at the end of the eleventh year for the various cases. As expected, the number of publications increases monotonically with increasing the publication rate. There are 30 publications for the case of rapidly decreasing production rate of "slope: -2," 110 publications in the case of constant production rate ("slope: 0") and 220 publications for the rapidly increasing production rate of "slope: +2."

The total numbers of citations (see Figure 2) show a similar trend. There are 10 citations for case No. 1, 260 for case No. 2, and 880 citations for the most rapidly increasing publication rate of case No. 6.

The trend of the CPP values (see Figure 3) is completely opposite to the trends of the total number of publications and citations. The CPP is the highest (CPP=10) for the "stop publishing" case. It decreases continuously with increasing the slope of the publication rate, reaching the lowest value (CPP=4) for the steepest increase of productivity considered in the case of "slope: +2." The calculated CPP values can be compared with the true citation frequency (one citation per paper per year) using CPP values normalized by the number of citation years (=10). These are shown in Figure 4. Obviously, there is no difference in the trends shown in Figures 3 and 4; only the scaling has changed. The value of the normalized CPP is one (as would be expected) only for the first "stop publishing" case. For the more productive research groups, the normalized CPP is significantly smaller than one, and it keeps decreasing with increasing productivity.

It is evident from this study that the CPP based on averages, as

![Figure 1. Total number of publications in the various cases (time period eleven years).](image-url)

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calculated in this study (and in Science Watch[^8] for example) does not represent the “impact” or research quality, since the impact is actually the same in all the cases studied here—one citation per paper per year. It definitely does not represent research productivity, since increase of productivity actually reduces the CPP. In the next section a modification of the CPP that eliminates the influence of the publication profile is proposed.

### WEIGHTED CPP

When the CPP is calculated for a given time period (as in the example presented), the papers published at the beginning of the period have a higher chance to be cited than papers published in later years. This inequality can be eliminated by assigning to each publication a weight according to the feasible number of years for its citation. Accordingly, in an evaluation that considers a specified time period of $n$ years, a particular paper that was published in the $i$th year is assigned a weight of $(n-i)$. To calculate the weighted CPP (WCPP), the total number of citations is divided by sum of the weighted publications (each publication is multiplied by its corresponding weight).

In the last column of Table 2 the calculation of the WCPP for the various cases is shown. In case No. 1 there is one publication in the first year, which should be included with the weight of $(11-1)=10$. Since there are ten citations of this publication the resulting WCPP is one. For the “slope: -2” case, there are ten papers in the first year with a weight of ten, eight papers in the second year with a weight of nine, and so on. The sum of the weighted publications is:

$$ (10 \times 10 + 8 \times 9 + 6 \times 8 + 4 \times 6 + 2 \times 5) = 260 $$

Since this is equal to the total number of citations, the value of the WCPP is also one in this case.

In Figure 4 the value of WCPP is presented together with the normalized CPP values. It can be seen that WCPP obtains the expected value of one for all the cases, in contrast to the normalized CPP, which obtains different values for the various cases. Thus, in the WCPP the influence of the publication profile on the citation statistics is eliminated, and it correctly reflects an “impact” of a single citation per paper per year. Therefore, the WCPP is much more appropriate to represent “impact” of research than the CPP.

### CONCLUSIONS

Using a simulation study, it has been shown that a CPP-based comparative evaluation of research groups of different publication profiles may yield absurd re-
EXPERIMENTS TO DEMONSTRATE CHEMICAL PROCESS SAFETY PRINCIPLES

BRIAN D. DORATHY, JAMISUE A. MOOERS, MATTHEW M. WARREN, JENNIFER L. MICH, AND DAVID W. MURHAMMER
The University of Iowa • Iowa City, Iowa 52242-1219

Apathy towards chemical process safety in the United States came to an abrupt end following the toxic methyl isocyanate (MIC) release from the Union Carbide India Ltd. pesticide plant in Bhopal, India, on December 2, 1984.12 The resulting MIC spread over a heavily populated area and resulted in the death of thousands. This incident led to passage and implementation of the Emergency Planning & Community Right-To-Know Act of 1987 and the chemical process safety amendments to the Clean Air Act of 1990 in the United States. In addition, the Center for Chemical Process Safety (CCPS), which is affiliated with the American Institute of Chemical Engineers, was founded in 1985 in response to the Bhopal incident. The CCPS is committed to developing engineering and management practices to prevent or mitigate the consequences of catastrophic events at chemical plants.

Recognizing the need for educating undergraduate chemical engineering students, CCPS, in a cooperative effort with engineering schools, initiated the Safety and Chemical Engineering Education (SACHE) program in 1992. SACHE provides teaching materials (e.g., slide/lecture sets, video lectures, problem sets, and instructional modules) to aid educators in incorporating safety into undergraduate chemical engineering programs. The SACHE instructional materials can either be used to incorporate safety into existing chemical engineering courses, e.g., using safety related problems from the SACHE problem sets, or as supplementary material for a dedicated chemical process safety course.

At the University of Iowa we have a dedicated required chemical engineering course that is taken by students during their junior year. We also incorporate problems from the SACHE problem sets into other chemical engineering courses. We believe that a dedicated chemical process safety course is highly desirable since it (i) allows coverage of material that would not fit well into existing chemical engineering courses, (ii) emphasizes the importance of chemical process safety, (iii) reinforces the importance of all chemical engineering fundamentals (e.g., thermodynamics, reaction kinetics, transport, and material and energy balances) to chemical process safety, (iv) provides an excellent review of the other chemical engineering courses, and (v) better prepares students for industrial employment. Major aspects of the chemical process safety course offered at the University of Iowa are summarized in Table 1. Additional approaches to incorporating chemical process safety into the chemical engineering curriculum can be found in the literature.3,4

The laboratory experiments listed in Table 1 give students hands-on experience with such issues as flammability limits, flash points, electrostatics, runaway reactions, explosions, and relief design. All of these issues are important in industrial processes. It is well known that most students are more

Brian D. Dorathy graduated from the University of Iowa in 1999 with a BS degree in Chemical Engineering. He was an undergraduate teaching assistant in the Chemical Process Safety course offered at the University of Iowa during the Spring 1999 semester.

Jamisue A. Mooers graduated from the University of Iowa in 1999 with a BS degree in Chemical Engineering. She was an undergraduate teaching assistant in the Chemical Process Safety course offered at the University of Iowa during the Spring 1999 semester.

Matthew M. Warren graduated from the University of Iowa in 2000 with a BS degree in Chemical Engineering. He was an undergraduate teaching assistant in the Chemical Process Safety course offered at the University of Iowa during the Spring 2000 semester.

Jennifer L. Mich graduated from the University of Iowa in 2000 with a BS degree in Chemical Engineering. She was an undergraduate teaching assistant in the Chemical Process Safety course offered at the University of Iowa during the Spring 2000 semester.

David W. Murhammer is Associate Professor in the Department of Chemical and Biochemical Engineering at the University of Iowa. He received his BS degree in Chemistry and his MS degree in Chemical Engineering from Oregon State University, and his PhD degree in Chemical Engineering from the University of Houston. He developed the Chemical Process Safety course offered at the University of Iowa and has taught it annually since its inception in 1996. His research interests include insect cell culture and bioreactor monitoring.
TABLE 1
Details of Dedicated Chemical Process Safety Course
(Additional details: <http://icaen.uiowa.edu/~cpsafety/>)

<table>
<thead>
<tr>
<th>Major Topics Covered</th>
<th>Reactivity</th>
<th>Fires and Explosions</th>
<th>Fire and Explosion Prevention</th>
<th>Relief Design</th>
<th>Hazard Identification</th>
<th>Risk Assessment/Reliability Engineering</th>
<th>Case Studies</th>
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</table>

**Textbooks**


**Safety Essay**

Students write an essay (1500-word maximum) regarding a topic relevant to chemical process safety consistent with the format requested for the SACHE-sponsored Student Essay Award for Undergraduate ChE Students.

**Project**

Group projects are performed in which students analyze safety issues relevant to the process of manufacturing the specific chemical assigned to them. A major aspect of the final report and oral presentation regards how inherently safer design concepts can be incorporated into the existing process.

**Homework**

There are weekly homework assignments.

**Quizzes**

There are weekly quizzes (generally 10-20 minutes). These seem to improve the learning process and to discourage student procrastination.

**Exams**

There are one or two midterm exams and a final exam.

**Laboratory Experiments**

- Flammability Characteristics
- Electrostatics
- Runaway Reactions/Relief Design
- Explosions/Relief Design

---

**TABLE 2**
Summary of Equipment

Additional comments and equipment costs (1999 estimates) are also given. (Prices are for Advanced Reactive System Screening Tool (ARST), successor to the RSST.)

<table>
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<tr>
<th>Experiment</th>
<th>Major Equipment Used</th>
<th>Comments</th>
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<td>Flammability</td>
<td>Miniflash FLP Flash</td>
<td>The flammability limits experiment also uses a personal computer for data acquisition and gas cylinders with gauges to charge the apparatus with the desired amounts of propane and air. In addition, a barometer can be used to correct for deviations from atmospheric pressure.</td>
</tr>
<tr>
<td>Characteristics</td>
<td>Model 4200, Petrolab Company, Latham, NY; ~$12,000</td>
<td></td>
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<tr>
<td></td>
<td>Flame Tec Flammability Limits and Data Acquisition System (Fauske and Associates, Burr Ridge, IL; ~$24,000)</td>
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<td></td>
<td>Electrode with accessories for high voltage (Model 6514, Keithley Instruments, Inc., Cleveland, OH; ~$4,000). Accessories include a Model 6103C Voltage Divider Probe, Model 6171 2 log to 3 log Triax Adapter, and Model 6102 Triax to UHF Adaptor.</td>
<td>These experiments are generally simple and require a few additional accessories commonly available in laboratories, as described in the main text.</td>
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<tr>
<td></td>
<td>Static Monitor (JCI-140, John Chubb Instrumentation, Cheltenham, England; ~$1,000)</td>
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<tr>
<td></td>
<td>Van de Graaf Generator (Stock # CR52-587, Edmund Scientific, Barrington, NJ; ~$500)</td>
<td></td>
</tr>
<tr>
<td>Runaway Reactions/Relief Design</td>
<td>Reactive System Screening Tool (RSST) (Fauske and Asso., Burr Ridge, IL; ~$19,600)</td>
<td>These experiments also require a computer for data acquisition and for running the vent sizing software. In addition, a nitrogen gas cylinder and regulator are needed to pressurize the RSST unit.</td>
</tr>
<tr>
<td></td>
<td>Vent Sizing Software Program (Fauske and Associates; ~$2,500)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flame Tec Flammability Limits and Data Acquisition System (Fauske and Asso., Burr Ridge, IL; ~$24,000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modified Hartmann Tube (Type MP-5, Adolf Kühner AG, Switzerland; ~$12,500)</td>
<td>The flammability testing apparatus requires a computer for data acquisition. The modified Hartmann tube does not require any accessories other than the test materials.</td>
</tr>
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</table>

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Winter 2001
and a copy of the raw data. Experimental write-ups given to the students at the University of Iowa can be found on the Chemical Process Safety course web site (see Table 1).

**Flammability Characteristics**

Prior to conducting these experiments students should be introduced to the importance of flash points and flammability limits. In addition, they should understand the relationship between these two parameters, i.e., the flash point of a pure substance is the temperature at which the concentration of flammable vapor in the gas phase is equal to the lower flammability limit (see Figure 1). These experiments will acquaint the students with methods used to determine flash points and flammability limits.

In our experiments we collected flash points for pure alcohols (methanol, ethanol, and 1-butanol), alcohol/water mixtures, and alcohol/alcohol mixtures. Data were collected with a Minijflash FLP Flash Point Tester (Table 2), an automated instrument that determines closed cup flash points. A manual Pensky-Marten flash point tester (Table 2) was also used to observe when a substance flashes. Data obtained from the automated instrument were used for analysis. Note that the data should be corrected for deviations from atmospheric pressure.

First, the measured flash points (FPs) for the pure alcohols were compared with accepted literature values. All of the experimental values were within 2°C of the accepted literature values, with the ethanol measurement typically within 0.5°C of the literature value (Table 3).

Second, the flash points were measured for different concentrations of alcohol/water mixtures. These values were first compared with values calculated assuming an ideal solution, i.e., determining the temperature at which the vapor pressure of the flammable component (alcohol) is equal to that of the pure component vapor pressure at its flash point (6, 8) (Table 3). The experimental values for the alcohol/water mixtures were consistently several degrees lower than the values obtained assuming ideal solutions. The largest difference between the experimental and calculated values occurred for the mixture containing 33.3 mole% 1-butanol, for which the calculated value was about 14°C higher. It should be emphasized, however, that in reality these solutions are nonideal. Therefore, the FPs were also calculated taking into account nonideal behavior. Briefly, liquid-vapor equilibrium data (9) for the alcohol/water mixtures were used to calculate activity coefficients ($\gamma_i = P_{alcohol}Y_i / P_{water}x_i$) at the corresponding liquid concentration ($x_i$). The FP was then calculated assuming that the activity coefficient is a function of concentration only. As shown in Table 3, the corresponding calculated values are all within 2°C of the measured values, with the sole exception of the 1-butanol ($x = 0.333$)/water solution, for which the calculated FP was 3°C higher than the measured value.

Third, the FPs were measured for different concentrations of alcohol/alcohol mixtures, specifically, methanol/1-butanol and ethanol/1-butanol mixtures. These measured values were compared to the theoretical values obtained from the intersection of the vapor pressure and lower flammability limits.

---

**Figure 1.** Diagram demonstrating the relationship between the flash point and lower flammability limit.

**TABLE 3**

Typical Flash Point (FP) Results

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<tr>
<th>Material Tested (mole fraction)</th>
<th>Typical Experimental FP (°C)</th>
<th>Calculated FP (°C)</th>
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<td>13* ---</td>
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<tr>
<td>0.000 0.000 0.667 0.333</td>
<td>18.0</td>
<td>15.9 ---</td>
</tr>
</tbody>
</table>

*Literature values obtained from reference 6.
curves on a plot of flammable vapor concentration versus temperature (Figure 1). For a given liquid phase concentration the vapor phase concentration of the alcohols can be calculated by assuming an ideal solution, i.e., by using Raoult’s Law. The lower flammability limit (LFL) of the mixture can be estimated by

$$LFL_{mix} = \frac{1}{n} \sum_{i=1}^{n} \frac{y_i}{LFL_i}$$

(1)

where $LFL_{mix}$ is the LFL for the mixture, $y_i$ is the mole fraction in the vapor phase of component i on a combustible basis, and $LFL_i$ is the LFL of pure component i at 25°C. Thus, it is assumed that $LFL_{mix}$ is not a function of temperature, i.e., it is a constant in Figure 1. This is a good assumption for the experiments discussed in this paper since the temperature effect on LFL is small over the relevant temperature ranges. It should also be noted that there is some controversy regarding the equation commonly used to estimate the effect of temperature on the LFL of a pure substance. The “concentration of flammable vapor” given in Figure 1 is the sum of the vapor phase mole fractions of all of the alcohols. The calculated values given in Table 3 are generally 2-3°C lower than the measured values for both alcohol mixtures. It is possible that the calculated values would agree more closely with the measured values if treated as nonideal mixtures. It is suggested that the students attempt to develop other methods of estimating the FPs of alcohol mixtures. In addition, the fact that the predicted FPs agree so well with the data may lead to overconfidence in this method by students. It is known that this method works satisfactorily at room temperature and pressure, but degrades considerably at increased temperature and pressure. Thus, this approach is applicable for product or raw material shipping (done at ambient temperature and pressure), but less applicable for process conditions.

The lower and upper flammability limits of propane were determined using a Flame Tec flammability limits and data-acquisition system (Table 2) that collects pressure-time and temperature-time data. Briefly, the FlameTec apparatus is charged with a known mixture of air and propane and ignition with a spark is attempted. If the mixture ignites, i.e., if an appreciable rise in pressure and temperature occurs, then it is within the flammability range. This process is repeated with a variety of propane concentrations to determine the flammability range. Typical LFL and UFL values obtained using this procedure are compared with literature values, as shown in Table 4. The experimental LFL value is consistent with the literature LFL, while the UFL literature values is approximately 1.0% higher than the experimental UFL range. More precise results could be obtained by using smaller incremental partial pressures of propane. In addition, it should be noted that flammability results can vary slightly based on the ignition device.

Once the LFL for a substance is known, its minimum oxygen concentration (MOC) can be estimated using

$$MOC = LFL \left( \frac{\text{Moles O}_2}{\text{Moles Fuel}} \right)$$

(2)

where LFL is the lower flammability limit, and the ratio is the stoichiometric ratio of oxygen to fuel for complete combustion of the substance.

Students were expected to address the following in their reports:

- Define the following terms and discuss how they are relevant to the experiment and industry: LFL, UFL, MOC, and flash point.
- Calculate the LFL, UFL, and MOC of propane and compare to literature values.
- How do the flash points obtained in the laboratory compare to expected values?
- Under what conditions would the results from this experiment not represent actual process results?

**Electrostatics**

A series of experiments was conducted to provide students with an improved understanding of the electrostatic charge accumulation that can occur in industrial processes. Most of these experiments were suggested by Crowl and/or Lüttgens and Glor. A high-impedance electrometer (Table 2) was used to measure electrostatic potential (V) and charge accumulation (Q). A high-impedance instrument is required for these experiments since electrostatics is a low current-high voltage phenomenon. Given V and Q, the accumulated energy (J) and capacitance (C) can be calculated by

$$J = \frac{QV}{2}$$

(3)

and

$$C = \frac{Q}{V}$$

(4)

One set of experiments was conducted to demonstrate electrostatic charge and/or voltage accumulation during the transport of materials. First, the phenomena were measured on a metal beaker isolated from ground (using a piece of teflon or styrofoam) into which substances were added in a variety of ways. Specifically, (i) water or a powder (e.g., cornstarch) was allowed to free-fall through air into the
beaker, (ii) water or a powder was poured down a plastic surface into the beaker, and (iii) water or a powder was poured down a metal surface into the beaker (see Fig. 2a). Second, the voltage and/or charge buildup resulting from recirculating diesel fuel through a metal filter (7-micron mesh size) isolated from ground was monitored (Fig. 2b). Third, experiments were conducted in which the accumulation of voltage and/or charge resulting from the agitation of a liquid in a metal vessel isolated from ground was monitored. Monitoring the dissipation of the accumulated charge following grounding of the vessel provides the means to evaluate a liquid's relative ability to dissipate charge (conductive liquids versus non- and semi-conductive liquids). This experiment was conducted with both tap water and diesel fuel, which are conductive and semi-conductive liquids, respectively.

The results of the above experiments can be analyzed qualitatively or quantitatively, or a combination of both. For example, monitoring charge and voltage accumulation for a given experiment can be used to calculate energy accumulation and capacitance, using Eqs. (3) and (4), respectively. The basic principles involved, however, can be sufficiently understood with a qualitative analysis. The dropping water/powder experiments were performed to compare different contact methods and the relative conductivities of different materials. Water poured down a metal sheet dissipates potential difference effectively due to the conductive nature of both materials. Water poured through air or down plastic demonstrates that when at least one material is a poor conductor (air or plastic), a charge separation and potential difference are observed. Since cornstarch is a nonconductive powder, charge separation is observed regardless of what additional materials or contact methods are involved. Recirculation of diesel fuel through an ungrounded metal filter demonstrates how contact between a semiconductive liquid and an improperly bonded and grounded filter can easily result in charge separation. Similar phenomena are observed in the agitation experiments, which directly contrasts the dissipative qualities of water and diesel fuel and suggests the importance of understanding the conductivity of various chemicals present in a given industrial process. An additional experiment could involve the addition of an antistatic agent to the diesel fuel in the recirculation experiment in order to observe ways to alleviate charge accumulation.

A second set of experiments was conducted to demonstrate charge accumulation on humans and the potential hazards thereof. First, the potential difference caused by removing a sweater or jacket and by using a Van de Graaf generator (Table 2) was measured and used to calculate the energy and capacitance using Eqs. (3) and (4), respectively. In addition, in each of these cases it can be determined whether enough energy is generated to ignite propane (see Fig. 3). In general, any charge accumulation exceeding 350 volts and 0.1 mJ is considered dangerous in industrial operations where flammable vapors are present. It should be emphasized that these experiments work best when conducted under low
humidity conditions, and when the insulating material is effective in isolating the lab participant from ground. This is particularly important for the Van de Graaf experiment.

Finally, a propagating brush discharge was demonstrated in a third experiment. This provides a dramatic visualization of releasing charge buildup. A propagating brush discharge is an energy-rich energy discharge in which a highly charged insulating surface (e.g., a film) is backed with a grounded conductor. The “feathery” discharge shown in Figure 4 is characteristic of this type of discharge. The demonstration uses a thin sheet of overhead projector plastic, a sheet of metal (approximately 1/4” thick), and an insulating block. Each of these listed materials was approximately 1 foot by 1 foot. The three materials were arranged as shown in Figure 4a. The metal sheet was connected via an insulated metal wire to the Van de Graaf generator (all wire connections were secured with electrical tape). In addition, two electrodes with sharp tips were grounded using insulated metal wire.

The experiment was initiated by turning on the Van de Graaf generator, which resulted in a separation of charge between the metal slab (which becomes positively charged) and the overhead plastic (which becomes negatively charged). While this charge separation is occurring, one of the grounded electrodes is held at a distance of approximately one cm from the overhead plastic. Results are best when the electrode is moved laterally across the entire area of the plastic sheet while the Van de Graaf generator is running.

While the charge separation is occurring, the experimenter should look and listen for sparks along the metal sheet, particularly at sharp corners. These sparks lead to premature charge dissipation and can diminish experimental success. An easy solution to this problem is to line the edges of the metal sheet with electrical tape prior to conducting the experiment.

Charge separation on the experimental setup is allowed to proceed for approximately one minute, at which time the Van de Graaf generator is turned off. The first grounded electrode is centered over the plastic sheet (still at a distance of approximately 1 cm), and the second grounded electrode is brought into direct contact with the edge of the metal sheet, as shown in Figure 4b. At this point, the metal sheet is grounded, leaving a large charge imbalance between the plastic sheet and the metal sheet, resulting in a propagating brush discharge through the first grounded electrode. The success of this experiment depends on developing a consistent routine; therefore, it is most effective as a demonstration instead of having each lab group attempt the experiment (though if time allows, students should attempt to recreate the experiment after the initial demonstration is complete).

Propagating brush discharges can occur with a voltage difference of 200 kV per meter of distance between the surface where a charge imbalance exists and the potential dissipation route (e.g., the first electrode in the discharge experiment above). A simple experiment to investigate this maximum potential difference involves unraveling a roll of overhead projector plastic. A field meter (see Table 2) or high-voltage probe used with a high-impedance electrometer (Table 2) is placed near the expected trajectory of the unrolling plastic. This distance should be estimated for calculation purposes. The end of the rolled plastic should be pulled quickly and with some force in order to observe a significant amount of unraveling, and the maximum voltage reading should be recorded. Results for the experiment varied between lab groups, but as much as 194 kV/m potential difference was developed in some runs.

After completing the above experiments, students were expected to answer the following questions in the results and discussion section of the report based on data obtained from the laboratory experiments:

- Describe the phenomenon of charge separation between two materials in contact.
- What are the important material properties being considered in the experiment (i.e., how does one material vary from another, and how do these differences affect experimental results)?
- Relate each experiment to a typical situation in industry, and discuss the difference of magnitude between industrial and lab scale scenarios.
- What are other ways that charge accumulation can occur in an industrial environment?
- What can be done to prevent and/or counteract charge build-up?

Runaway Reaction/Relief Design

This experiment provides the students with an understanding of how to characterize a runaway reaction and how to collect and use data to size a relief vent for an industrial scale.
reactor of a given volume and given charge of reactants. To demonstrate these principles, the reaction of 2 moles of methanol with 1 mole acetic anhydride, i.e.,

\[ 2 \text{CH}_3\text{OH} + \text{O(COCH}_3\text{)}_2 \rightarrow 2 \text{CH}_3\text{COOCH}_3 + \text{H}_2\text{O} \quad (5) \]

is investigated using a calorimeter (Reactive System Screening Tool [RSST], Table 2). Briefly, methanol and acetic anhydride are charged into the RSST and the temperature is increased at a constant rate of 2°C/min. Once an onset temperature is reached, the exothermic reaction self-heats and a runaway reaction occurs. Two separate tests are conducted: the first is conducted at a low pressure (representing the set pressure of a field scale vessel) and the second is conducted at a high pressure (representing the maximum allowable working pressure of a field scale vessel). The actual pressures used for these tests can be changed according to the type of vessel that is being simulated, and they also depend on the pressure of nitrogen available. Results included in this paper use pressures of 15 and 150 psig for the low- and high-pressure tests, respectively. The RSST, interfaced with a computer, collects temperature-time and pressure-time data. When the reaction "takes off," a rapid increase in the temperature and pressure are observed, as demonstrated in Figure 5 for the methanol/acetic anhydride system at an initial pressure of 15 psig. It should be noted that, ideally, the low-pressure test should be conducted at constant pressure for the duration of the experiment (i.e., pressure should be monitored and relieved under a chemical fume hood when necessary in order to maintain a vessel pressure consistent with the chosen set pressure of the relief device).

In the data presented above pressure was not regulated, which affects the observed tempering temperature. These pressure and temperature data can be used to generate heat rate and pressure rate curves for relief vent sizing by hand calculations or by the Vent Sizing Software Program (VSSP, Table 2). Whether heat-rate or pressure-rate data are used in vent-sizing calculations depends on the type of runaway reaction that occurs (vapor, gassy, or hybrid). In a "vapor" runaway reaction, the vapor is produced by components vaporizing due to the heat of reaction; in a "gassy" runaway, the gas is a product of the reaction; and in a "hybrid" reaction, both phenomena occur. For the vapor system of methanol and acetic anhydride, heat-rate curves for both the high- and low-pressure tests are sufficient. Figure 6 shows typical heat rate results for the methanol/acetic anhydride reaction system.

Two calculation methods for vent sizing were considered. The hand calculation was performed using

\[ A = 1.5 \times 10^{-5} \frac{m \dot{T}_s}{F P_v} \quad (6) \]

where \( A \) (m²) is the vent area, \( m \) (kg) is the charge of reactants to the field scale vessel, \( \dot{T}_s \) (°C/min) is the self-

heat rate due to exothermic reaction at the specified set pressure \( P_v \) (psia), and \( F \) is the flow reduction factor that accounts for piping connected to the relief vent (venting directly to atmosphere has a flow reduction factor equal to one). Equation (6) assumes two-phase flashing flow and assumes 20% overpressure (absolute) during venting. The
second calculation method used the VSSP. The theory behind VSSP calculations and Eq. (6) is similar and leads to similar results. Figure 7 shows typical VSSP input for the methanol/acetic anhydride system.

Inputs such as set pressure, back pressure, vessel volume and reactant charge are defined in the laboratory objectives (and can be modified for each lab group). Liquid specific heat and density are estimates based on reactant composition at set pressure. Vapor density does not play a significant role in calculations, thus it is assigned a value of 1 lb m/ft³. The Clausius-Clapeyron equation is used by the VSSP when latent heat is significant role in calculations, thus it is assigned a value of 1 lb m/ft³.

Table 3 summarizes the results obtained from the RSST data in Figures 5 and 6 for a field scale vessel with a volume of 1000 gallons and a methanol/acetic anhydride charge of 1500 kg (2:1 mole ratio).

The students compared and discussed the results they obtained from the hand calculation and the VSSP. Typical results for hand calculations for this system (1500 kg reactants, 1000 gal vessel) ranged between 17 and 24 in². VSSP results for the same system ranged between 11 and 13 in². Error in the above results can be attributed to a number of factors. For example, self-heat and tempering values are read visually from charts, and are susceptible to some error. Also, the fact that the low-pressure experiment was not conducted at a constant pressure introduces error in the tempering temperature, and subsequently the self-heat rates. The VSSP and hand calculations both use the original system pressure of 15 psig in the calculation.

The student can also complete a kinetics analysis of the RSST data (this is especially applicable to a course in chemical reaction engineering). First, the students can determine the activation energy using the straight-line data shown in Figure 6. Second, given the kinetics of the reaction, the students can calculate the temperature at which the runaway reaction should begin and compare their calculated results with the experimental data.

The students are expected to answer the following questions in the results and discussion section:

- What type of system is the methanol/acetic anhydride reaction (vapor, gassy, or hybrid)? How are the data collected used to determine this?
- What is the tempering temperature of the system?
- Which relief sizing results (hand or VSSP calculation) should be used? Why?
- What characteristics of the RSST design might prevent the results from being used for a larger reactor vessel?
- Will a larger vessel runaway faster or slower than the RSST? Why?
- Define the following terms and relate each to the RSST experiment: set pressure, back pressure, and maximum allowable working pressure.

Explosions/Relief Design

The purpose of this experiment was to demonstrate the principles of dust and gas explosions. First, a Modified Hartmann Apparatus (Table 2) was used to demonstrate dust explosions and to aid in understanding the dust classification system. Briefly, powder is loaded into a tube and a continuous spark is created from two electrodes

![Figure 7. Typical VSSP input data for the methanol/acetic anhydride system.](image)
placed approximately one-half inch apart. Compressed air at seven bar (gauge) is suddenly released, which suspends the powder inside the tube and over the spark. An explosion (i.e., a sudden flash of fire) occurs under the proper conditions. Measurements are taken during the explosion and the output from the control box is 0, 1, or 2. If the output is a 1, then the dust is classified as a St-1 class dust. Anything other than a 1 means that more sophisticated equipment is needed to determine the classification. Dusts are classified into St classes based on their deflagration index, Ks. The Ks for a dust increases as the robustness of its explosion increases.[11] Three powders were tested—flour, cornstarch, and baking soda, in the amount of 1200 mg each. Results are summarized in Table 6.

The following questions were answered in the discussion part of the report.

- When do dust explosions occur?
- What characteristics must a dust have to be explosive?
- What are the typical lower and upper explosion limits for dusts?
- What were the physical differences between the three powders and how did these attribute to whether or not they created an explosion?
- Describe the classification system of dust explosions.

The second part of the experiment used the Flame Tec flammability limits and data acquisition system (Table 2) to examine gas phase explosions. Pressure-time and temperature-time data were collected for a propane explosion. A propane concentration of 4.5% was used, which is equivalent to a partial pressure of 0.7 psi propane in the vessel. The pressure-time data collected can then be used to calculate the gas deflagration index $K_s$ for propane using the “Cubic Law”

$$K_s = \left(\frac{dP}{dt}\right)_{max}^{1/3} \frac{V}{181} \quad (8)$$

where $V$ is the vessel volume and $(dP/dt)_{max}$ is the maximum rate of pressure increase. It should be noted that $K_s$ for a given material is dependent on several factors, including the composition of the material, mixing in the vessel, the vessel shape, and the energy of the ignition source.[11] The pressure-time data can also be used to scale up the effects of an explosion to a field-scale vessel.

In addition to the above, the following questions were answered in the laboratory report.

- What is the concentration of the propane in the vessel? Is it inside the flammability range for propane?
- Was the explosion in the vessel a detonation or a deflagration? Why?
- Calculate the $K_s$ for propane.
- Under what conditions would the results of this experiment not represent actual process results?

### CONCLUSIONS

Chemical process safety has become a critical component of chemical engineering education, e.g., it is very important to industry and is required by ABET 2000. The importance of chemical process safety in the undergraduate education of chemical engineers is certainly consistent with having a course, preferably required, dedicated to this topic. In the absence of a dedicated course, however, it is essential that safety concepts (flammability characteristics, electrostatics, runaway reactions, explosions, and relief design) be incorporated somewhere in the undergraduate curriculum. The experiments described herein provide a means for introducing these important topics into the curriculum in a hands-on manner that is known to enhance the learning process.

### ACKNOWLEDGMENTS

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### REFERENCES

Publication Rate Profiles
Continued from page 35.

sults. The CPP is the highest for the less productive department and the lowest for a department with the most rapid increase of research productivity. It is also evident from this study that, in contrast to the popular belief and depending on the publication profiles involved, the CPP does not necessarily represent the “impact” and quality of research.

A new “weighted” CPP has been proposed, which eliminates the influence of the publication profile on the citation statistics and as such, is much more appropriate for measuring research impact. Obviously, in order to yield valid results, the WCPP must be referred to the world average WCPP of the particular research field.

The simulation study demonstrates once again that a comparative evaluation of research quality and productivity cannot be based on a single criterion. While the WCPP has herein proven to be more reliable in measuring “impact” than the CPP, it still may rank a stagnant (or even a declining-production research group) and a group of a rapidly increasing productivity the same. The WCPP can be heavily influenced, just as the CPP can, by additional factors such as the number of co-authors, the number of different research groups involved, and hidden self-citation. Therefore, it is always essential to look beyond various citation measures.

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In Memoriam
Sami Selim

Sami Selim was born in Cairo, Egypt on January 24, 1942, and passed away in Denver, Colorado, on June 27, 2000. He was educated as an undergraduate at the University of Alexandria (Egypt), and earned his MS in chemical engineering from Carnegie-Mellon and another MS in mathematics and a PhD in chemical engineering, both from Iowa State University. Prior to joining Colorado School of Mines (CSM) in 1982, he held faculty appointments at the University of Petroleum and Minerals in Dhahran, Saudi Arabia, and at Texas Tech. He was a member of the Chemical Engineering Education Publications Board for the last decade.

While his health problems limited his physical activity in later years, his mental activities remained extremely strong. We at CSM will remember “Dr. Sami” as the consummate professor: a brilliant lecturer, superb theoretician, gifted problem solver, and a world-class example of the phrase “absent-minded professor.” He will be sorely missed by all of his friends and colleagues in the department, and by those students who were privileged to have benefited from his wit and wisdom, both inside and outside of the classroom.

A list of adjectives that might be used to describe Sami would almost certainly include scholar, educator, mentor, leader, colleague, and friend.

Scholar • A “learned person - one trained in a special branch of knowledge.” Sami’s knowledge of transport phenomena and applied mathematics was unparalleled in our department and university, and he was highly respected throughout the world in his areas of expertise.

Educator • Sami taught essentially every course in our undergraduate curriculum and every transport- and mathematics-oriented course in the graduate program. In his teaching career, he earned outstanding teacher awards four times.

Mentor • Perhaps Sami’s greatest contribution was in his ability to mentor graduate students and faculty. He literally poured himself into a quest to instill a love of knowledge and discovery in our students.

Leader • Sami emerged as a true leader at CSM as a result of the work he did to introduce flowsheeting and computer-aided chemical process design throughout the undergraduate curriculum. During the mid to late 1980s, Sami spent a great deal of time working with Aspen Technology and Phillips Petroleum, learning how to perform computer-aided process simulation and then helping the faculty introduce this technology in every course in the ChE curriculum. Associated with this effort, he emerged as a leader in defining the content of what we teach in chemical engineering at CSM.

Colleague and Friend • All of us at CSM have memories of Sami that will last a lifetime. We all have treasured “Sami stories” that we won’t forget anytime in the near future.

Sami is survived by his wife, Barbara. A scholarship fund in Sami’s name has been established in the CSM Foundation. Please contact Bob Baldwin <rbaldwin@mines.edu> for instructions on donations.

Robert M. Baldwin
James F. Ely
E. Dendy Sloan
DYNAMICS OF A STIRRED-TANK HEATER

Intuition and Analysis

J.A. ROMAGNOLI
University of Sydney • Sydney, New South Wales, 2006, Australia

A. PALAZOGLU, S. WHITAKER
University of California • Davis, CA 95616

A common example in chemical engineering textbooks on dynamic modeling and control is the stirred-tank heater illustrated in Figure 1. If the tank is treated as perfectly mixed, it represents a simple process that allows for a straightforward derivation of the governing equations, and it helps to illustrate the use of constitutive equations in developing dynamic process models. The assumptions involved in the analysis are typically justified by common sense and practical insight. With them, one arrives at a model that can be used for demonstrating dynamic behavior through simulations and for testing feedback control concepts.

This problem has found its way into the majority of dynamics and control textbooks, and in these textbooks we observe three different approaches to the analysis. The first approach is represented by the assumption of constant flow rates (thus constant holdup), which simplifies the problem considerably. Seborg, et al., derive the model equations but also focus on the constant holdup problem in the text. The second approach is by Harriott and by Pollard, who consider flow variations but still assume constant holdup. The book by Stephanopoulos provides a third approach in which the holdup is not constant and perturbations are present in both inlet and outlet flowrates. This leads to the multivariable control of both the holdup and the temperature in the tank.

If the volume of fluid in the tank is allowed to vary (in response to variations in the outlet flowrate), the coupling between the mass and energy balances generates a curious, non-trivial problem that has not been fully recognized in the literature. Specifically, the dynamic behavior of the stirred tank heater appears to contradict, at least initially, our intuitive reasoning, leading to an incorrect interpretation of the expected behavior.
In the next section, we first define the problem and offer an intuitive description of the dynamic behavior of the process. Next, in an effort to provide a rigorous explanation of why we should expect a dynamic response contrary to our intuition, we derive the dynamic model of the stirred-tank heater process, carefully delineating all the steps and the assumptions involved. Finally, we offer some insight into the correct intuitive interpretation of the analytical result.

**PROBLEM DEFINITION**

Figure 1 depicts a stirred-tank heat process. The purpose of this unit is to provide heating for a process stream, thereby increasing its temperature before being supplied to a downstream unit. The heat provided is denoted by $Q$. In the schematic diagram, $F$ and $T$ represent a stream flowrate and a stream temperature, respectively, and the subscripts “in” and “out” refer to the inlet and outlet streams. We assume that there is a valve placed at the outlet flow stream, which can be adjusted to affect the tank level.

**Intuition**

Now, let us perform the following thought experiment. Assuming that the system is initially at steady state, we shall increase the outlet stream flowrate, thereby creating a transient process in which the level in the tank decreases, as illustrated in Figure 2. The heat supplied to the system, $Q$, remains constant, and we want to know how the temperature of the outlet stream responds to this change. Typically, intuition leads to the suggestion that the outlet stream temperature will increase since less mass is now being heated in the tank. If we decrease the outlet stream flowrate, the level in the tank will increase, as illustrated in Figure 3. The typical intuitive interpretation of this transient process is that the outlet stream temperature will decrease because more mass is now being heated in the tank.

Both these intuitive interpretations of the dynamic response of the stirred-tank heater are incorrect, as can be shown by a careful analysis of the system. We must note that if one changes the inlet flowrate instead of the outlet flowrate, the above reasoning leads to the correct answer, and thus there is a fundamental difference in the way each flowrate affects the temperature in the tank.

To summarize our survey of intuitive judgments concerning the influence of changing the outlet flowrate, we note that almost everyone believes that changing the outlet flowrate will change the outlet temperature. In addition, most believe that increasing the flowrate will cause an increase in the temperature, while decreasing the flowrate will cause a decrease in the temperature.

**ANALYSIS**

**Modeling**

To develop the dynamic model of the stirred-tank heater, we make use of the macroscopic mass and thermal energy balances\(^{[2]}\) for a moving control volume. These are given by

$$\frac{d}{dt} \int_{V(t)} \rho dV + \int_{A(t)} \rho (v-w) \cdot n dA = 0 \quad (1)$$

$$\frac{d}{dt} \int_{V(t)} \rho c_p (T-T_{\text{ref}}) dV + \int_{A(t)} \rho c_p (T-T_{\text{ref}}) (v-w) \cdot n dA = - \int_{A(t)} (q + q_R) \cdot n dA + \int_{V(t)} \left( T \frac{\partial p}{\partial t} + p \cdot \nabla T \right) dV \quad (2)$$

in which the moving control volume, $V(t)$, contains the fluid in the stirred tank as illustrated in Figure 1. In terms of the liquid depth, $h(t)$, and the cross-sectional area of the tank, $A$, the control volume can be expressed as

$$V(t) = Ah(t) \quad (3)$$

At the gas-liquid interface, the kinematic condition requires that

$$v \cdot n = w \cdot n \quad (4)$$

while at the liquid solid interface we have

$$v \cdot n = w \cdot n = 0 \quad (5)$$

Use of these two conditions, and the assumption that the density can be treated as a constant, allows us to express the macroscopic mass balance as

$$A \frac{dh}{dt} = F_{\text{in}} - F_{\text{out}} \quad (6)$$

in which $F_{\text{in}}$ and $F_{\text{out}}$ represent the volumetric flow rates entering and leaving the system. To be explicit, we express $F_{\text{out}}$ according to

$$F_{\text{out}} = \int_{A_{\text{exit}}} v \cdot n dA \quad (7)$$
In our treatment of the thermal energy balance, we neglect the reversible work, \( T \partial p / \partial t \), and the viscous dissipation, \( \tau : \nabla v \), so that Eq. 2 takes the form

\[
\frac{d}{dt} \int \rho C_p (T - T_{ref}) dV + \int \rho C_p (T - T_{ref}) (v - w) \cdot n dA = - \int (q + q^R) \cdot n dA
\]

If the only significant heat transfer to the system is caused by the heater, the heat-transfer term on the right-hand side of this result can be expressed as

\[
- \int (q + q^R) \cdot n dA = Q
\]

in which \( Q \) is positive when heat is transferred to the system.

Assuming that the variations of \( \rho \) and \( c_p \) are negligible, and making use of Eqs. 3 through 5, allows us to write Eq. 8 in the form

\[
\rho c_p \left( A h(t) \langle T \rangle - q_{ref} \right) = \rho c_p F_{in} (T_{in} - q_{ref}) - \rho c_p F_{out} (T_{out} - q_{ref}) + Q
\]

Here the volume averaged temperature, \( \langle T \rangle \), is defined by

\[
\langle T \rangle = \frac{1}{V(t)} \int V(t) T dV
\]

and since \( \rho c_p \) can be treated as a constant, Eq. 10 can be rearranged as

\[
\frac{d}{dt} \left[ \rho c_p A h(t) \langle T \rangle - q_{ref} \right] = \rho c_p F_{in} (T_{in} - q_{ref}) - \rho c_p F_{out} (T_{out} - q_{ref}) + \frac{Q}{\rho c_p}
\]

Carrying out the differentiation on the left-hand side leads to

\[
A h(t) \frac{d}{dt} \langle T \rangle + \langle T \rangle - q_{ref} \frac{d}{dt} A h(t) = F_{in} (T_{in} - q_{ref}) - F_{out} (T_{out} - q_{ref}) + \frac{Q}{\rho c_p}
\]

Equation 6 can be multiplied by \( \langle T \rangle - q_{ref} \), leading to

\[
A \frac{d}{dt} \langle T \rangle - q_{ref} = F_{in} (T_{in} - q_{ref}) - F_{out} (T_{out} - q_{ref})
\]

and when this result is subtracted from Eq. 13, we obtain a simplified form of the macroscopic thermal energy balance. The macroscopic mass and thermal energy balances represent the governing differential equations for the fluid depth and the volume-averaged temperature in the stirred tank. We list these two results and the initial conditions as

**Mass**

\[
A \frac{dh}{dt} = F_{in} - F_{out}
\]

**Thermal Energy**

\[
A h(t) \frac{d}{dt} \langle T \rangle = F_{in} (T_{in} - \langle T \rangle) + \frac{Q}{\rho c_p}
\]

**Initial Conditions**

\[
h = h^o \quad \langle T \rangle = \langle T \rangle^o \quad F_{out} = F_{in} \quad t = 0
\]

The driving force for the dynamic behavior is the outlet stream flowrate, which is a function of time, \( t \),

\[
F_{out} = F_{in} + \Delta F(t) \quad t \geq 0
\]

At this point, we identify the state variables and constant parameters as

**State Variables:** \( h \) and \( \langle T \rangle \)

**Constant Parameters:** \( A, \rho c_p, Q, F_{in}, \) and \( T_{in} \)

It may not be obvious on the basis of Eqs. (15) through (18), but the solution for the volume-averaged temperature for this process is given by

\[
\langle T \rangle = \langle T \rangle^o \quad t \geq 0
\]

**Solution**

In practice, the change in the outlet stream flowrate, \( \Delta F \), is a function of \( h^o - h(t) \), and thus the outlet stream flowrate can be expressed by

\[
F_{out} = F_{in} + \Delta F[h^o - h(t)] \quad t \geq 0
\]

Use of this result in the macroscopic mass balance given by Eq. (15) leads to

\[
A \frac{dh}{dt} = -\Delta F[h^o - h(t)] + \frac{Q}{\rho c_p}
\]

This result can be subtracted from Eq. (16) to obtain

\[
A \frac{d}{dt} \left[ h(t) \langle T \rangle - q_{ref} \right] = -\Delta F \langle T \rangle - \langle T \rangle^o
\]

If we identify the temperature difference according to

\[
\Theta = \langle T \rangle - \langle T \rangle^o
\]

the initial value problem for \( \Theta \) takes the form

\[
f(t) \frac{d\Theta}{dt} = -\Theta
\]

I.C. \( \Theta = 0 \quad t = 0 \)

Here the time dependent function, \( f(t) \), is given by

\[
f(t) = \frac{A h(t)}{F_{in}}
\]

and the solution to Eqs. (26a) and (26b) is

\[
\Theta = 0 \quad t \geq 0
\]

This leads to the result listed earlier as Eq. (19), which is often considered to be counter-intuitive.

The forms of Eqs. (26a,b) and the solution given by Eq. (28) usually create a little skepticism; however, we can...
transform the initial value problem to a more familiar form in order to make the solution more appealing. We begin by letting \( \tau \) be a function of time defined by
\[
\tau = \int_{\eta=0}^{\eta=1} \frac{1}{f(\eta)} \, d\eta \quad f(t) \neq 0
\]
(29)
This transformation leads to
\[
\frac{d\Theta}{dt} = \frac{d\Theta}{dt} = \frac{d\Theta}{dt} f(t)^{-1}
\]
(30)
and the initial-value problem given by Eqs. (26a,b) takes the form
\[
\frac{d\Theta}{dt} = -\Theta
\]
(31a)
I.C.
\[
\Theta = 0 \quad \tau = 0
\]
(31b)
Clearly, the solution to this initial-value problem is given by Eq. (28).

**DISCUSSION OF DYNAMIC BEHAVIOR**

The source of the seemingly counter-intuitive behavior of the tank temperature when the outlet stream flowrate is changed lies in the key assumption of *complete mixing* in the tank. To provide a purely intuitive confirmation of either Eq. (19) or Eq. (28), we construct special processes in which the fluid depth in the tank either decreases or increases.

**Case of Outlet Stream Flowrate Increasing** • This situation can be best visualized as illustrated in Figure 4 where the tank height is decreasing as a secondary stream removes fluid from the tank while the primary outlet flowrate remains equal to the inlet flowrate. Note that the secondary stream flowrate is time-dependent and will vanish as time increases and a new steady state is established. In this case, removing additional fluid from the tank will only decrease the fluid level in the tank without changing the temperature of the fluid in the tank. The temperature of the fluid in the tank is determined by the rate of heat transfer, \( Q \), that is delivered to the incoming fluid.

**Case of Outlet Stream Flowrate Decreasing** • This situation can be visualized as in Figure 5, where the tank height is increasing as the flow is diverted back to the tank. Again, the diverted stream is time dependent and will vanish as time increases and a new steady state is achieved. Returning some of the outlet stream to the tank will increase the fluid depth in the tank; however, the temperature of the outlet stream is identical to the temperature in the tank and returning a portion of this fluid to the tank will have no influence on the temperature in the tank.

Rather than use the constructions illustrated in Figures 4 and 5 to enhance our intuition, we could simply observe that the energy delivered to the system, \( Q \), is used to raise the temperature of the inlet stream from \( T_{in} \) to \( T^0 \), and the disposition of the outlet stream has no influence on this energy-transport process. Thus, the heated fluid in the tank can be disposed of more or less rapidly, giving rise to a change in the fluid depth in the tank, without influencing the temperature in the tank.

**CONCLUSIONS**

The dynamic behavior of a stirred-tank heater challenges our intuition when mass and energy balances are considered simultaneously. The perfect mixing assumption creates a decoupled dynamic response when changes in the outlet flowrate are considered. We have presented a rigorous model of the process and have offered an explanation as to why we should expect this seemingly counter-intuitive phenomenon to occur.

**REFERENCES**

AN ANALYSIS OF ENROLLMENT CYCLING IN ChE

R. RUSSELL RHINEHART
Oklahoma State University • Stillwater, OK 74078-5021

Nationally, chemical engineering BS graduation rates cycle with about a 13-year period and a 2.2-to-1 high-to-low amplitude. The past 1.5 cycles are shown in Figure 1, a plot of the national production of BS ChE graduates from the past twenty years. The numerical value for the abscissa, Academic Year, is the calendar date for the end of the academic year (1990 represents the academic year from the fall of 1989 to the summer of 1990). This study also considered the 20-year history of 30 individual U.S. ChE programs, chosen to represent a diversity of program types. All 30 schools cycle substantially in phase with the national data, and each with about a 5-to-1 ratio. Figure 2 presents a graph of the trends and visually suggests that the BS-ChE rates at all schools appear to cycle in phase with the national data. Local events and the statistics of small numbers make the individual school amplitudes greater than the national amplitude.

In a more quantitative analysis of the data, Table 1 presents correlation coefficients, \( r \), of the BS graduation rate at each school to the national rate. All \( r \) values larger than 0.34 are significant at the 95\% level for the number of data points, and all but 2 of the 30 schools observed have \( r \) values larger than 0.34. Even schools with smaller \( r \) values have a BS production rate that is somewhat correlated to the national trend. Coefficient of Variation (CV) results are also presented in the table for each school. CV is the ratio of the standard deviation to the average. All schools have a CV of about 0.4, and this common value indicates that all show the same relative cycling amplitude. There are no trends of correlation coefficient, CV, or cycle amplitude with ChE program size. The data reveal that the phenomenon is national and affects all schools in unison and to the same relative degree.

The cycling is a source of great discomfort, and it hurts chemical engineering education. During periods of peak BS production rates, students who graduate without job offers feel betrayed. Parents also become upset and challenge the

---

**Figure 1.** National BS-ChE rates.

**Figure 2.** BS-ChE rates, national and various schools, versus year.
ChE program’s adequacy. This is not a good way to generate the alumni allegiance necessary for program development.

At the other extreme, in periods of low BS production rates, State and University administrations often question the need for an expensive ChE program. This often leads to inadequate resources for lab upgrades and difficulty in retaining faculty positions. Both lab equipment and faculty positions are critical for sustained program excellence, especially during peak enrollment periods. Further, during low production periods, industry must inflate entry-level salaries and make an excess number of job offers to attract a sufficient number of employees. While this is advantageous for the new graduates, it results in an uncomfortable salary compression and resource-allocation problem for industry. Finally, during periods of low BS supply, companies withdraw from recruiting at schools, making it difficult to later reestablish on-campus recruiting and to maintain continuity in other forms of industrial support.

The cycling has lasted as far back as data could be found. Figure 3 shows the BS-ChE history at Oklahoma State University (OSU) from its first graduate in 1921 to the present. The 13-year cycling period is evident since about 1930, after the start-up phase of the program.

It appears generally accepted that the number of students who choose engineering is influenced by the job opportunities and the salary levels. In his study of overall engineering enrollments from 1965 to 1995, Heckel[3] reports

*Engineering enrollment trends are shown to differ significantly from those of undergraduates as a whole and to exhibit little correlation with trends in high school graduation data. Freshmen engineering enrollments show very strong correlation with factors which might indicate to high school students the magnitude of their personal economic gain such as on-campus industrial recruiting*

---

**TABLE 1**

<table>
<thead>
<tr>
<th>School</th>
<th>Max Number of BS ChE</th>
<th>Min Number of BS ChE</th>
<th>Ratio Max to Min</th>
<th>Std. Dev.</th>
<th>Average</th>
<th>CV</th>
<th>Ratio of Range to Avg.</th>
<th>Number of years of data</th>
<th>Correl. Coef.</th>
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Winter 2001

Figure 3. BS-ChE production at OSU.
Most engineering students seem to make an economically rational decision, seeking to maximize the probability of attaining a high-salary job upon graduation, and this one incentive seems to control trends in engineering enrollments. It appears that in certain engineering programs (aerospace, chemical, materials, and nuclear) the cycling behavior is unusually large.

If we can understand the mechanism, then we can hope to design a cure. This paper presents data that refute the commonly accepted mechanism, a novel view of the mechanism for cycling, a model that expresses the same behavior as the national data, needs for further study, and possible solutions to the cycling problem.

**REFUTING THE COMMONLY ACCEPTED MECHANISM**

Enrollment cycling is a symptom: there is a cause, and a successful cure for the cycling must affect the cause. If we accept that the cause is “A” when it is actually “B,” and invest efforts to cure “A,” we will not alleviate the cycling. This study appears to refute the commonly held cause.

The traditional view is that enrollment swings are demand driven—they reflect student choices in response to the changing ChE job demands by the economy. In this view, low matriculation rates are due to low numbers of job offers in prior years (due to a low economy), and then low matriculation leads to low BS production about four to five years later. There is, however, no correlation of national engineering enrollment to national economic factors. 

Figure 4 provides additional data and reveals that there is no correlation of the national BS-ChE cycling to the national economy, as measured by the gross domestic product (GDP). In Figure 4, the GDP in constant dollars is plotted with the national BS-ChE production; it reveals that the BS-ChE oscillations are seemingly independent of, and much larger than, changes in the national economy. In addition, economic factors (that would indicate job opportunities for chemical engineers) have shown a relatively steady growth, with neither 2-to-1 cycling nor a regular 13-year period.

One may suppose that while the overall national economy does not cycle, sectors do—and that the employment demand by specific industry sectors causes enrollment cycling for schools that supply those sectors. But if this were true, then Gulf-Southwest schools, which are significantly coupled to the oil and gas industry, would cycle independently of Northwest schools, which are significantly coupled to the pulp and paper industry, etc. Enrollment at all schools, however, regardless of region or orientation, cycles in phase, with the same relative amplitude and with a regular period.

As a supporting refutation of the impact of local school data on school cycling, see Figure 5. Figure 5a plots the ChE freshmen-class size versus the BS-ChE rate at OSU, and Figure 5b plots the same data versus the national BS-ChE rate. The four-year lag led to the strongest correlation for both scatter plots. The correlation coefficient, $r^2$, stated on each graph, along with the observable closeness of the data to the regression lines, indicates that OSU freshmen-class-size data correlates much better to the national data than to our local data. Figures 5c and 5d reveal similar relationships for the total OSU undergraduate ChE enrollment. Student choices at OSU correlate much better to national data than to local data. The same probably holds true for other schools.

The commonly held view of the cause for cycling is in contrast to data. Let’s consider mechanism “B.”

**HYPOTHESES CAUSE FOR THE CYCLING**

The mechanism for ChE enrollment cycling hypothesized here is not based on employment demand. It is based on BS-ChE supply. The cycling is supply driven. The cycling causes the cycling. The job market is relatively steady, but when there is an excess supply of graduates there is a low probability of finding a job, and high school students do not choose ChE. Subsequently, when graduation rates are low, there is a very high demand for ChEs, which is exaggerated by industrial competition for the limited supply. This attracts a flood of students. Further, the cycling mechanism hypothesized here is not based on local events; it is based on the national data.

Proposed here: the enrollment process is inherently unstable because of the controllers—the “high gains” in student and recruiter choices.

The hypothesized incentive that drives enrollment for chemical engineering is a perception, by high school students, of the attractiveness and availability of jobs at the national level. Attractiveness includes a combination of factors that appeal to young adults and includes both professional and personal attributes such as salary, social stature,
and academic challenge. Availability of jobs is indicated by the fraction of students who obtain jobs upon graduation, but it is based on recent-past data, not on the projected future.

Informal discussions and analysis with OSU ChE students reveal several features of the decision process that control enrollment. It appears that selecting ChE as a major is sensitive to the perceived incentive of a high salary. Students who can complete a degree in chemical engineering can probably complete a degree in any of a number of chemical science degree programs. These students probably had a chemistry course in high school, but they are not familiar with any of the professions within the chemical sciences, and the marketing material for the various professions promises challenging, enjoyable, and socially important careers. As a result, their main incentive in the choice of a college major is probable entry into a high-paying job upon graduation.

Within the chemical science careers, chemical engineering is the degree program that leads to the highest employment salary. When the probability of getting a ChE job is high, students rush into the program. But the program is very demanding, and when the probability of getting a job appears low, these same students choose other majors in an economically rational decision. One source of data that students might use to make that decision is the employment-upon-graduation data that ChE schools submit each May/June to AIChE, the Council for Chemical Research, and other agencies. The data is nationally compiled and published about a year later, through a variety of private, public, and not-for-profit agencies. When high school seniors begin to consider college choices they have access to this year-old (and older) data. The mechanism proposed here is that employment-upon-graduation data from one year affects the decision of matriculates two years hence and affects the BS graduation rate four to five years later. This suggests a cause of the six-to-seven year swing from high to low BS rate and the 13-year cycle period.

MODEL

A model of this mechanism is developed from a simple population balance on students in each class-year category. It reveals the natural instability of the process, the 13-year period, the BS production rate cycling, and the national coordination. It also produces statistics that match many features of OSU ChE enrollment data. The model for a single school is presented first.

One aspect of the model is the constitutive relation that describes the number of high school students entering the university who declare chemical engineering when they matriculate. This number is a function of the incentive to study chemical engineering. In what follows we use the term $\alpha$ to represent the fraction of university matriculates declaring ChE. In this study we use the number of job offers per BS-ChE graduate as the incentive. We feel fairly certain of three

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Figure 5a. Freshman+other class size vs. OSU BS rate (lag 4).

Figure 5b. Freshman+other class size vs. national BS rate (lag 4).

Figure 5c. OSU ChE total enrollment vs. OSU BS-ChE rate (lag 5).

Figure 5d. OSU ChE total enrollment vs national BS rate (lag 5).
points on the \( \alpha \)-versus-incentive curve. When there is zero incentive (zero job offers for any ChE graduate), then there will be no ChE matriculates. When the incentive is at a maximum (experience indicates that this might be three job offers per BS-ChE) then matriculation rates will be at a maximum. At OSU this maximum in matriculation is about twice the nominal value that seems to be 0.006 freshmen ChEs per OSU freshman. So, \( \alpha (\text{incentive}=3)=0.012 \) at OSU. Finally, a nominal matriculation rate occurs when the incentive is nominal, defining \( \alpha (\text{incentive}=1)=0.006 \) (at OSU).

We also feel fairly certain of the general shape of the \( \alpha \)-versus-incentive curve. Regardless of the incentive, \( \alpha \) will not be much greater than 0.012, the apparent maximum. There is only a portion of the population that leaves high school with either the preparation or willingness to study chemical engineering, and regardless of the incentive the remainder will not choose ChE as a major. Consequently, \( \alpha \) should asymptotically increase to its upper limit of about 0.012. This feature and the three points define an S-shaped curve, which we model as

\[
\alpha = 0.01679 \cdot \exp(-1.0397/r)
\]

where the variable “\( r \)” represents the incentive, the ratio of job offers per graduating BS. The relation is illustrated in Figure 6.

There is no pretense that this equation for \( \alpha \) is precise, or that the ratio of job offers per BS is the true and exclusive measure of the incentive to study ChE. It appears to be reasonable. Neither is there a claim that this equation is necessary to stimulate cycling. One could certainly argue that alpha should be based on a moving average of job-offers to BS ratio, and the reader is encouraged to explore such options. In this study any number of reasonable models for \( \alpha \) seem to lead to cycling. The feature that is important, however, is that this is a nonlinear, high-gain relation.

The model is composed of a population balance on the number of students in each class-year. The number of entering ChE freshmen is \( \alpha \) multiplied by \( hs \), the number of high school students matriculating at the university. In what follows, the symbol “\( N \)” will represent the number of ChE students, and the modifiers, “1,” “2,” ..., “5,” will represent the class year (freshman, sophomore, ..., through second-year senior). The modifier “\( R \)” represents students who are repeating the class-year. Accordingly, Eq. (2) presents a population balance of students taking freshmen courses. The subscript “\( i \)” represents the academic year. In Eq. (2), the number of people in the freshman ChE class is the sum of the number of new matriculates plus the number of students who were freshmen last year and who are still taking freshmen-level courses this year. Some are repeating; some are still ramping up from inadequate high school preparation; some are on a reduced course load plan. To reflect both the communications delay in presenting the “job market” to high school seniors who are choosing a major and the persistence of the recent past “job market” history, we use the average value of alpha of the two and three preceding years.

\[ N_{1i} = 0.5(\alpha_{i-3} + \alpha_{i-2})hs + NIR_{i-1} \]

(2)

Based on historical data at OSU, the number of students remaining in the freshmen-level ChE courses in year, NIR, is approximately 20% of the freshmen in the previous year. The formula used is

\[ NIR_i = 0.2 N_{1i} \]

(3)

It appears, from data from various sources, that approximately 60% of the ChE freshmen would progress into the sophomore-level class; and at OSU, this number seems independent of either class size or incentive. Transfers into the sophomore level is conceived as students who have spent a year in another major and have been enticed by the incentives to switch into chemical engineering. It appears reasonable to model this as 10% of previous year’s \( \alpha \) multiplied by \( allso \), the total number of sophomores at the university. Including a term for students that repeat the sophomore class, the population balance for students in the sophomore class is

\[ N_{2i} = 0.1\alpha_{i-1} allso + 0.6 N_{1i-1} + N2R_{i-1} \]

(4)

The number of people that remain in the sophomore-level classes was also modeled as 20%. The equation is

\[ N2R_{i} = 0.2 N_{2i} \]

(5)

The equation for the number of students in the junior year is similar to that for the sophomores. OSU data shows that about 65% of the sophomores proceeded into the junior year, and that this proportion, too, is independent of events. It was also assumed that transfers only accounted for 1% of the previous year’s alpha multiplied by \( alljr \), the total number of juniors at the university. The equation is

\[ N_{3i} = 0.01\alpha_{i-1} alljr + 0.65 N_{2i-1} + N3R_{i-1} \]

(6)

OSU data indicate that about 5% of the juniors repeat their junior year. The equation for the number of repeating juniors is
It was assumed that there are no transfers in the senior year. Approximately 93% of the OSU ChE juniors enter into the senior year. The equation that describes the population balance around the senior class is

\[ N3R_i = 0.05N3_{i-1} \]  

(7)

It was assumed that only one percent of the senior class would have to repeat the year. The following equation was used to describe the number of seniors that repeat:

\[ N4R_i = 0.01N4_i \]  

(9)

OSU data shows that approximately 54% of the seniors would go on to a fifth year where they would take courses off of the critical path that they postponed earlier. The following equation is used to describe the number of students entering the 5th year:

\[ N5_i = 0.54N4_{i-1} \]  

(10)

The number of graduating seniors, NG, is modeled as the number of 5th-year students plus 42% of seniors:

\[ NG_i = N5_i + 0.42N4_i \]  

(11)

The missing 4% of the seniors seem to drop out of the OSU program for varying reasons unrelated to academic ability.

The number of available employment positions, Jobs, is modeled using a random walk starting from a nominal steady-state number. The driver for the walk is a Gaussian-distributed random variable, NID(\( \mu = 0, \sigma \)), where \( \sigma = 0.04 \times \text{Jobs} \). Generated by the Box-Mueller method, the job market equation is

\[ \text{Jobs}_{i} = \text{Jobs}_{i-1} + \sigma \sqrt{\log(r_1)} \sin(2\pi r_2) \]  

(12)

Here, \( r_1 \) and \( r_2 \) are independently and uniformly distributed random numbers on the interval 0 to .999... This is a simple model, and to prevent some realizations from leading to a negative job market, the lower value is limited to at least one job per year.

There seem to be any number of disturbances or disturbance models that lead to the limit cycling. These include perturbations on the number of high school students or the model’s retention coefficients. This simple economic driver was chosen for this example.

The number of jobs offered to BS ChEs may be different than the number of positions available. In a "buyer’s market," in times when there are more graduates than there are available positions, companies make one offer for each position. But, in a "seller’s market," in times when there are more job openings than there are available graduates, companies often make more offers than there are positions in an attempt to fill all of their positions. The bigger the supply deficit, the more aggressive are recruiting efforts; however, in fear of over staffing, it appears that companies limit themselves to no more than two outstanding offers per open position. Here the variable \( \beta \) represents the ratio of job offers per available position. If it's a “buyer’s market,” \( \beta = 1 \). If it’s a “seller’s market,” this study models \( \beta \) as rising with the square of the ratio of jobs per BS degree, but with an upper limit of 2.

\[ \beta_i = \left( \frac{\text{Jobs}_{i}}{\text{bs}_{i}} \right)^2 \]  

(13)

The number of job offers is then \( \beta \) multiplied by the number of jobs available for that year.

\[ \text{Jobers}_{i} = \text{Jobs}_{i} \beta_i \]  

(14)

The number of job offers per BS ChE is then used to calculate the incentive, alpha. Other models for \( \beta \) that express similar behavior produce equivalent cycling behavior.

Initial values for N1, N2, N3, N4, and N5 were chosen to start the class sizes at a steady state, with NG equal to the number of employment positions.

These equations lead to a fractional number of students in any category. In this simulation all values that represented the number of people were rounded to an integer.

**SINGLE-SCHOOL MODEL RESULTS**

Figure 7 shows the dynamic response of a single-school model, from the initial steady state to the limit cycle, as instigated by one realization of the random perturbations in the job market. Notice that the variation in BS production rate cycles regularly, irrespective of the number of jobs. Notice also that the amplitude of variation in the BS rate is much greater than the amplitude in the number of jobs. This was one realization; any other, independent of driver, shows the same eventual behavior.

Figure 8 reveals the behavior of the number of students in each class year for a smaller school. The population of each class shows a phase lag of one year from the previous class and the expected reduction in numbers due to attrition.

**TEN-SCHOOL MODEL RESULTS**

The single-school model was expanded to ten schools. In one study, shown in Figure 9, each of the ten schools is independent in the sense that: 1) the “local” student’s incentive was purely based on the local incentive (job offers to BS ChEs at that particular school), and 2) the perturbation in the local job market for each of the ten schools was independent of the nine other local markets. The sizes of the ChE programs ranged from an average BS-ChE rate of 12 to 45 per year, and no significant impact on the period of the oscillation was observed. All were about 13 years. Noticeable, though, is that all schools found their own phase in response to the independent realizations of the disturbance, cycling was not coordinated.
To model a national influence, to generate correlation between schools such as is observed in the national data, the calculation of $\alpha$ is weighted to represent both “local” and the ten-school “national” job offers per BS incentive. It was found that the more national influence, the more the cycles became “in phase.” At only a 20/80 national/local weighting, Figure 10 shows that all ten schools become “locked” in phase in spite of independent random behavior in the local job markets, and independent initial behavior.

**DISCUSSION**

Results of model explorations not shown here reveal that the cycling phenomenon is independent of all reasonable adjustments in model coefficients. There were only two features that seem to have a tempering influence on the cycling phenomena; these being the students’ and the employers’ response to the jobs/BS ratio—modeled here as alpha and beta. If there is a cure for the cycling phenomena, it seems grounded in tempering human reaction to a perceived personal impact.

This is a simplistic, deterministic model that assumes all students share a common, time independent, region independent stimulus-response mechanism. While this study does not answer many important questions, and while it cannot claim to be a definitive exposition on individual student behavior, it does provide multifaceted, circumstantial evidence of a mechanism that leads to enrollment cycling.

Perhaps characteristics of a degree program that exhibits cycling are:

- A difficult program, both conceptually and time demanding, that can only be passed by a small number of the population who have the innate ability, self discipline, and adequate preparatory training.
- A program with specialty subject matter that is of interest or attraction to a small portion of the population.
- A degree that leads to very high starting salary, social status, and/or secure lifestyle.
- A degree that leads to a career that is relatively non-understood by the student, and where salary therefore dominates the possible influence of all other possible incentives or connections to the student’s personal values.

If these characteristics lead to cycling, then there may be actions that we can take to alleviate the cycling. One approach would be to collect data on employment based on graduate status four months after graduation, and exclude data on graduates without permanent work status. It appears not that we produce...
too many BS graduates; it appears that we produce more than are demanded by on-campus recruiters. Most of those unemployed upon graduation find jobs within several months after graduation, when they are free of the capstone course demands and have the time to search for employment. Some others choose graduate or professional school. If the employment data reflected employment rates about four months after graduation, then the apparent probability of landing a job might always be attractive, and cycling might be tempered.

Additionally, perhaps professional societies and government agencies that are accountable for rational system behavior and educational excellence, could shape the awareness of the societal benefits that come from chemical engineering, and thereby have the career appeal to personal values other than just economic gain. Then, fewer matriculates would be so greatly influenced by the apparent job demand, and enrollments would be more level.

Another tempering action might be to reveal this cycling phenomenon to high school students and counselors so that they make matriculation decisions based on the future, not the recent past, job market.

The model and data presented here provide indirect evidence to support the mechanism; but there is no direct, credible evidence to validate the hypothesized mechanism, the human response, or to evaluate possible cures. It appears that questions such as the following need to be answered.

1. What are the general characteristics of degree programs, or characteristics of the people, or nature of the environment that lead to cycling? Is there a commonality of cycling phenomena for degree programs with those common characteristics?
2. What is the primary incentive for high school and transfer students to choose ChE as a major?
3. What is the model for the fraction of college-bound students choosing ChE as a function of that incentive (alpha in this study)?
4. Is it possible to shift the ChE enrollment incentive to other professional or conscience attributes (social stature, commitment to the environment, commitment to human health, commitment to improve U.S. competitiveness, etc.) by a marketing campaign, and thereby reduce the number who choose ChE for probable salary, and thereby reduce the cycling amplitude?
5. What mechanisms create the information that becomes the basis for student choices? Are they professional society surveys of job salary and job satisfaction, professional society surveys of the number of students with jobs upon graduation, etc?
6. What mechanisms convey the information that becomes the basis for student choices? Are they hearsay, older siblings, friends, family, local employers, high school counseling pamphlets, Internet data banks, Department of Labor statistics, Society Publications, etc?
7. What is the industrial recruiting response to over- and under-supply of BS-ChE candidates for the number of job openings (beta in this study)?
8. How do students, parents, faculty, administrators, and employers view the effects of the cycling? What is the magnitude of the cycling problem (perhaps as indicated by the economic and personal impacts on society)?

CONCLUSIONS

Maximization of probable high-salary employment remains accepted as the driver for student choice for enrollment in chemical engineering. However, data refute the commonly held view that the "economy," the industrial job market demand for BS-ChEs, is responsible for ChE enrollment cycling. Hypothesized here, the perception of job opportunities by college matriculates is influenced more by enrollment swings than the economy. Changes in the supply of BS-ChEs dominates the supply-to-demand statistics, and hence enrollment. Enrollment cycling is supply driven. A primitive model of the mechanism expresses multiple aspects of national and local data. The model reveals that the dynamic system is inherently unstable, that enrollments tend to a limit cycle, and that student and recruiter response to the supply-to-demand for BS-ChEs is the source of the instability. A better understanding of this mechanism may lead to solutions; but, since national statistics appear to drive the perception, it appears that any cure must be implemented by the agencies that create national perception.

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

COOPERATIVE EDUCATION
A Key Link Between Industry and Engineers in the Making

TANYA BRADBURN
2053 21st Street SE, Apt. S • Hickory, NC 28602

A complex metamorphosis must take place before an engineering student understands what it really means to be an engineer. Like most processes, there are many paths to achieving the desired final result. This article considers not only my actual experiences in that respect, but also reflects on my discussions with many peers over the years—so it is more than just a memoir of my passage along this path to understanding.

In high school, the process toward understanding often begins upon learning that mathematics and science are tools of a mysterious profession called “engineering.” It is not unusual to find that when some of the “smart” people in the graduating class announce their plans to pursue that profession, other students will often find themselves pulled in the same direction. In my case, by the beginning of my senior year in high school I had decided that engineering was the path I wanted to follow. Despite this early decision, when I entered college I still had only the slightest idea of what an engineer’s real role in society was or what the typical day-to-day duties of an engineer really were.

The second stage of metamorphosis occurs in the first engineering class when one is challenged to “think like an engineer.” At this juncture, the class divides into two types of students. Type I students are extremely intuitive and seem to be able to see processes in their minds without ever having been in a plant, while Type II students can do the math and have intuitive skills, but can’t visualize the process. I was definitely a Type II student.

Cooperative education, summer internships, or part-time undergraduate research can eventually help Type II students such as myself to connect what we study to what it is that real engineers do, e.g., solve problems. Most universities have a freshman class that considers and explains some of the differences between engineering fields. In my case, however, this introductory course was extremely vague. For such a course to be really useful to the student, I feel it should thoroughly define each engineering discipline. For each department, there should be specific examples of the types of assignments a student might expect. Tours of companies employing various types of engineers could be included to allow students to see where they might expect to work after having been in a plant.
graduation, and a chance to hear an engineer from each environment explain what he or she does would be extremely useful students by helping them make informed decisions about the course of study to follow. The co-op experience naturally incorporates such opportunities for those students, like myself, who participate. Practically speaking, however, I believe co-op opportunities come too late to be useful to many of the Type II students who have become disenchanted in the first three semesters on campus.

Stopgap measures incorporating some of the most desirable components noted above are needed in order to reduce the loss of students experienced as a result of the nonspecific introductory courses offered at the beginning of their educational experience. A good beginning would be to simply show the students pictures of equipment that engineers use in each of the disciplines. For example, chemical engineering students could be shown pictures of separation equipment, computer control equipment, and microelectronic and bio-processing equipment. This would help provide students with a visual idea of the huge range of opportunities available in the field. Also, at least one field trip, complemented by on-campus presentations by articulate practicing engineers, could and should be included in such a course.

A key common element in all these options is the opportunity for a student to see, firsthand, the exciting impact an engineer can have in the workplace. The co-op option appears to be the most practical approach for most students. This conclusion is based on the reality of operation in the time-constrained environments present in companies and universities. The companies that have committed to a bona fide co-op program understand its value as a screening and recruiting tool and are willing to invest in it. Such companies actually have a framework in place to support the program.

For any off-campus opportunity, knowing the answers to the following questions will help students know what to expect and how to prepare for their work assignments:

- Is the potential assignment part of an on-going established program in the company, or will you be the guinea pig?
- Has there ever been a co-op before in the area of the company where you will be working—can you contact prior participants?
- Does the company have a year round co-op program, so you aren’t disadvantaged in access to

Despite this early decision [to go into engineering], when I entered college I still had only the slightest idea of what an engineer’s real role in society was or what the typical day-to-day duties of an engineer really were.

class sequences needed for your graduation?
- Will you be paired with an actual mentor?
- Are there housing accommodations? If the company reserves apartments for co-ops/interns, are they furnished?
- How will your salary typically change as you complete rotations?
- Do you get vacation days?

Some of the questions may sound inconsequential, but they aren’t. Shuffling back and forth from campus to plant to campus without breaks gives students very little time to digest their experiences. Fitting into an existing optimized structure designed to accommodate students is a huge ad-

vantage in terms of the ultimate benefits to participants.

Maintaining such a framework is a significant contribution made by companies that are truly committed to co-op programs. Frameworks for moving and housing, as well as for other placement issues, is less common in so-called internships, since they are typically discontinuous and are centered around the summer months. Moreover, comments by internship participants suggest that such assignments often involve more ad hoc “mentor” relationships, as compared to co-op assignments.

The third option, undergraduate research, is another area of opportunity I have had experience with, and I will consider its benefits after focusing on the off-campus co-op benefits. While undergraduate research is highly desirable, the time commitment involved in trying to accommodate all undergraduates on campus via this route seems to be unreasonable in typical educational institutions.

As noted above, co-op assignments are quite effective because they give students an empowering insight into what can ultimately be done with their degrees. Such insight can give students the momentum to overcome hurdles along the way to acquiring their degree and can ultimately increase the
number of students who actually graduate.

Co-op work can also have second-order advantages. In my case, it forced me to leave the safe surroundings of familiar people and places. It put me into a new state, into a new home, and into a completely different environment. Without a doubt, pursuing a co-op job at Eastman Chemical Company in Kingsport, Tennessee, was one of the best decisions I had ever made. I had always lived in the Raleigh-Durham area, and moving to another state to work was an unsettling decision, to say the least. I was five hours from home when I drove by Eastman, or the “Big E,” on the way to my first apartment, and my mouth hung open the entire time as I drove past the plant. I had never seen such a plant before—the Kingsport Division is one of the largest chemical plants in the US. I remember thinking as I drove past it, “I have just made the biggest mistake of my life!!!” I simply wasn’t prepared for the smells of a chemical plant, the sight of the looming distillation columns, the reactors, and what seemed to be smoke (actually steam) swirling in the air.

To be honest, at the time I didn’t know what a distillation column or a reactor looked like. The boxes that I had drawn on engineering paper to represent such equipment in no way approximated the sights, sounds, and smells of an actual plant. I often think of how disconcerting it would have been if I had never worked on a co-op job, and if the first time I saw a chemical plant was after graduating as a BS engineer. Even if introductory classes had included pictures of a distillation column, I believe a Type II student such as myself would be unprepared for what it is really like to see one in a plant. In any case, however, it would have been more reassuring to at least know what I was looking at.

During my first co-op rotation, I worked with a separations group on a high-priority adsorption project for feed purification. Sometimes, I would work from 7 a.m. to 11 p.m. to meet our project objectives, but in spite of the long hours, it was exciting and challenging to be working on a real problem. For my second term, I worked in Cellulose Esters doing compressibility and percent solids analysis, and for my third rotation, I worked on optimizing the sludge system for the polymer division, working with several crews of operators. The reason for describing my co-op experience here is to show that no college course could possibly simulate what it is like to work with other operators, to actually be in a plant, or to work on a truly stressful project where the results mattered. It is a very different experience from just working for a grade!

Contact is made with students from many different schools during one’s work cycles, and based on conversations with these peers over the years, I have reached a number of conclusions about the strengths and weaknesses of educating chemical engineers. The following paragraphs elucidate a few of my thoughts about steps that could be taken that would greatly enhance the educational experience of students.

After students select an engineering specialty, regardless of whether or not they know what they are getting into, more practical applications should be included to complement the theoretical backgrounds they receive in the classroom. While in some cases, such practical teaching may not be economically possible, more can usually be done and it can be done much earlier.

Specifically, simple qualitative experimental illustrations would be useful, even when the students don’t completely understand every detail and equation needed to describe the situation. For instance, seeing a distillation column concentrate a dye from a feed stream is impressive and offers motivation to learn why it works; seeing a microelectronic part made or a bio reactor work can inspire the student to learn more about complex reactions and mass transfer phenomena. Connecting these exciting processes to the need to learn about chemical engineering fundamentals can make the student want to learn about these subjects. It seems to me that there is no real reason why some of these practical motivational aspects cannot be integrated more effectively into our formal education.

I know that senior-level engineering courses demonstrate some of these practical applications. In my senior design class, we were assigned to work in groups of 3-4 and were given a chemical to produce. Our assignment was to research the chemical in patents and textbooks and even to contact companies to develop a process for making the chemical. While designing the process, we had to perform energy and mass balances to track our components in producing the desired product at the necessary rate. We also had labs where we had hands-on experience with reactors, distillation columns, heat exchangers, etc. The point is that students would benefit more from some type of practical-application exposure throughout their education, rather than packing it all in at the end of their schooling. Even short demonstrations and group projects, when done earlier in the curriculum, would be more satisfying and valuable.

Can something be learned and transported back to campus from industrial, co-op, and intern experiences to enrich the learning experience of all students—even those who never leave campus? I believe so—especially in the area of computer skills and the need to better integrate their development throughout the curriculum, principally through the use of homework assignments.

There are at least four computer programs that are essential for a practicing chemical engineer to be familiar with: Excel, Aspen, PowerPoint, and Word. Most employers, even those found in co-op jobs, expect an employee to be competent with Excel. It seems to me that skills taught on campus in the use of these software programs should lead, rather than lag behind, those that are demanded in an industrial setting. This is often not the case, however.
Throughout their campus careers, students should build steadily on the sophisticated application of tools such as Excel. A good practice to follow is to teach the use of Visual Basic programming—that skill can then be used with Excel in later courses after students master the simple elements of Excel in their freshman course. While co-oping, I often needed to add data to a spreadsheet with over 700 rows, and it goes without saying that editing a spreadsheet that long can be very time-consuming. But (fortunately) an engineer in my group showed me some simple programming in Visual Basic that showed that deleting spaces between data on such a huge spreadsheet need not be done by hand at the expense of hours. From my co-op experiences, I learned that being a good engineer requires being able to optimize time expenditures. Spending hours editing spreadsheets that can otherwise be done more efficiently is not good time management.

Besides learning basic spreadsheet skills, students should learn how to analyze large data sets. During two of my co-op terms, I had to analyze someone else’s data, even though I didn’t know all the details about the process related to the data. I now understand that one doesn’t need to be an expert in all of the process details to gain insight about why something is not going well with the process. A systems engineering perspective should be introduced and emphasized early in the curriculum in my opinion. Assignments should be given where only a brief description of the process is provided with a spreadsheet containing a large amount of data. The assignment should be to analyze the data and then decide which data should be considered. I believe that most practicing engineers would agree that statistics (which is necessary in data analysis) should be required for all engineering students.

In addition to Excel, Aspen (the unit operations simulator) is a key program and should be integrated into more of the chemical engineering curriculum. I had two weeks of Aspen during my second engineering class, and after that class, I never used it again in school. Perhaps it will surface again in the final design course, but Aspen would have fit well in several courses prior to that. Ideally, assignments could be given requiring integration of Aspen and Excel—this does happen in the real world of co-ops.

Two additional easy-to-use tools, PowerPoint and Word, also deserve some consideration. Both of these programs can be used by anyone who can turn on a computer, but to use them effectively takes practice. Given the intense pace in industry, imprecise communication guarantees that problems will occur. At the end of each of my rotations, I had to give a formal presentation in front of my peers, hiring managers, and whoever else wanted to attend. It takes experience to organize and present information in front of a large audience when you are under a spotlight and have to use a microphone, but the thought that a good idea that can’t be communicated is wasted must always be at the forefront when planning one of these presentations. I must also add that hearing your own voice echo without quivering in such a situation gives you confidence in your ability to give a presentation anywhere and to anyone after that, so the effort is worthwhile.

Before closing, I would like to mention an additional experience vehicle that already exists on campuses that could be invaluable in assisting the student’s metamorphosis to engineer. Increasing student-faculty interactions may sound like a simple idea, but while it may be obvious, it is not simple to do well. Our student chapter of the AIChE had a program in which juniors were paired with seniors in their major, and seniors were paired with a professor to create a mentor-mentee relationship. The problem with this simple but excellent idea is that often nothing happened. For instance, when I participated in it, a meeting was set up for students to meet the professors who had been assigned to them as their mentor—but none of the professors showed up!

We all accept that there are many demands on a professor’s time, and such a mentorship program is simply one more demand that the professor didn’t volunteer for, which probably places it low on the priority list. Nevertheless, if professors more actively participated and actually showed interest in programs such as this, students would benefit enormously. Ideally, the contact would provide exposure to the professor’s research program, and could possibly include some actual research experience for the student. This experience could give the student a more balanced perspective, enhancing the industrial co-op and internship experiences, to draw upon when considering the options available after graduation.

It took a bit of determination on my part to find that such an “on-campus co-op” experience was available. After my industrial co-op, I eventually worked for one of my engineering professors over the summer. The project involved growing bacteria that harbor a specific esterase that we wanted to recover. The professor took an active interest in my career and educational goals, which was an attitude that I had not seen in a teacher since high school. Such a personal relationship goes a long way toward allowing students to discover what they really want to do in life and what they need to do in order to develop the skills for pursuing their goal. I found that simply having an intelligent, experienced, and patient individual to bounce questions off of was enormously helpful in allowing me to frame my long-term plans. In fact, this role is the common element present in both successful industrial or successful campus co-op mentoring. This component catalyzes the organization of all the facts and experiences that are jumbled together in a typical “standard” undergraduate experience. It is one truly essential element that turns a bewildered student into a self-assured graduate engineer.
STUDENT MOTIVATION, ATTITUDE, AND APPROACH TO LEARNING

Notes From a Novice Teacher

EDUARDO VIVALDO-LIMA
Universidad Nacional Autónoma de México • México D.F., México

Professors are faced with outstanding-, average-, and poor-performance students every day in every class, but it seems that only a few try to understand what is wrong with the lower-end students and do something to help them. The natural tendency is to think of them as lazy or immature, or perhaps to view them as students who are in the wrong discipline. While some of them might indeed be immature or lazy, or misplaced, others could be failing courses in spite of their best efforts and are often in danger of dropping out of the course, or even dropping out of school.

When I think back to my days as an undergraduate and remember some of the smart and capable classmates who dropped out of school, I marvel that I managed to continue and to succeed when they did not. While the reasons are many and complex, some thoughts come to mind immediately—I was lucky enough to have several excellent teachers at different stages in my education, and they had a great influence on my academic and professional choices. I was exposed to different teaching styles throughout my college years and was able to take the best from each of them.

Some of my friends and relatives had the misfortune of having extremely poor teachers or badly organized courses at crucial stages of their education, with the result that they became discouraged or confused and eventually lost the will to continue their education. One friend from high school who had extremely good grades, dropped out of the university after one term in chemistry. She found that the impersonal teaching style of her college professors contrasted poorly with the cooperative teachers we had in high school, and it made a big difference in her own attitudes. While she was doing well (better than average), she was frustrated and none of the professors took the time to give her the reassurance she needed.

I am frequently impressed with the insight and intuitive understanding my own wife has of physical and chemical phenomena, in spite of her proclaimed dislike of “theoretical” explanations. She could have been an excellent chemical engineer, but she had “boring” chemistry teachers in high school and then in college she came face to face with the attitude (still prevalent) that women are not good at science—so she chose a different educational path. There are still professors who have different standards for men and women, claiming that “female chemical engineers will most likely end up staying home” while male chemical engineers would “most likely become field practitioners” and thus require a much more rigorous education. The sad truth is that many students with the potential to succeed are discouraged from doing so. In Felder’s words,[1] “There is nothing wrong with the raw material” (when talking about the quality of American students)—it seems that the educational system itself has been adversely affecting many of them.

This situation does not have to continue. Professors can do many things to promote students’ learning and to help them discover the best in themselves. Professors should focus on motivating students, adapting their teaching styles as necessary to nurture and promote the intellectual growth of their students.
students. They should strive to help students rise to the top.

This is easily said, but how can it be accomplished? To answer that question, a short literature review on motivation, learning, and teaching styles follows, and a compilation of recommendations from distinguished chemical engineering educators is given. Finally, my personal perspective will be given in two ways: first, the description of my strategy for effective teaching, despite being new in the profession, and second, a retrospective analysis of the experiences gained during my first two years as an associate professor at the National Autonomous University of Mexico.

MOTIVATION FOR LEARNING

It is usually accepted that motivated students are easier to teach—that students who are interested in learning do, in fact, learn more. Professors should encourage and take advantage of students’ motivation to learn. An optimal motivational level should be sought and established right from the course beginning. Since motivation and commitment are personal matters, what can be done to motivate the class as a whole? Cashin[1] proposes capitalizing on the students existing interests; relating the course to the students’ interests whenever possible; explaining in detail the relevance of the course, using problems, case studies, examples, etc.; discussing the ways in which the teacher finds the course interesting; finding out which topics are of most interest or value to the students; including some optional or alternative units; encouraging alternative learning methods (e.g., lectures, discussions, independent study, etc.) when possible.

Ericksen[2] notes the negative effect on motivation when there is a conflict between the teacher and students over course objectives and content. In small classes it is not particularly difficult to negotiate this conflict, but in large lecture courses the objectives are operationally defined by the procedures used in evaluation and grading. In large classes, the teacher makes most of the decisions as to what is learned and when it is learned. The principle of a performance-oriented course is not compromised and the advantage of participation is gained when students mark out a subset of objectives with which they want to become involved. Initial responsibility for drafting objectives, however, rests with the teacher, who has the knowledge of both the discipline and the available resources.

The learning environment present in a university can shift students from an interest focus to a course focus. In other words, students who are used to a high level of commitment and have high expectations for intellectual stimulation can be disappointed with the actual levels of each course offered in their university, to the point that getting “passing grades” becomes their main objective.[3]

Professors have to deal with a wide range of students; some are highly motivated and will succeed regardless of the subject matter, teaching effectiveness, or class size. But in nearly every class there are also those students who are “at risk,” who suffer from poor motivation, low self-esteem, or a low sense of personal control. Menec and Perry[4] propose two ways to help these students: (1) professors should function as attributional retrainers; i.e., they should modify students’ (mis)perceptions of their successes and failures by using an attributional retraining technique, and (2) there should be a proper use of comments about students’ performance and abilities.

PERSONAL PREFERENCE IN LEARNING (LEARNING STYLES)

Students learn in many different ways. Some prefer abstraction, others prefer facts. Some want details, others want the entire picture. Some think in terms of pictures and charts, others in terms of words, and still others in terms of symbols and equations.[5] Every human being has a preferred style. Woods[6] has recently published a detailed and interesting review on personal preferences in learning and provides a number of ideas on how to improve learning by accounting for the student’s personal preference in learning. Felder[7] has also critically reviewed the literature on learning and teaching styles. Moreover, he stresses the importance of helping students build their skills in both their preferred and less-preferred modes of learning. To do so, it is important to teach using techniques or material adequate for all the categories of learning styles. This is called “teaching around the cycle.”[8]

Different authors classify learning styles in slightly different ways. Woods[6] proposes three categories to classify learning styles. In the first category he includes those elements of learning style that are “robust,” those that cannot be changed: (1) Jungian or Myers Briggs with their four dimensions for processing information; (2) visualizer/symbolizer/verbalizer, or drawing/equation/words (DEW), which refers to the preference for memorizing and thinking about information; and (3) Kirton’s adaptor-innovator options for applying creativity. In a second category, he includes those styles that may or may not be possible to change: (4) serial versus holistic preference for processing information; and (5) inductive versus deductive preference for processing. In a third category he includes those styles that can be changed through training or experience: (6) Piaget’s levels of development; (7) Perry’s levels of attitude toward learning; (8) Kolb’s learning cycle; and (9) Entwistle and Ramsden’s
deep-versus-surface processing.

The explanation of these different learning styles and examples of how they manifest among students can be found elsewhere.\textsuperscript{7-12} What is worth mentioning here is Woods' list of ideas on how to facilitate learning in a way that takes into account learning preferences.\textsuperscript{7} To develop awareness, he proposes we

- Identify our own learning preferences since teaching and testing will be highly influenced by our own style
- Help students identify their own learning preferences and discuss the implications of each style
- Help students become more understanding of learning-style differences.

To cater to individual student's learning styles, Woods proposes

- When presenting information, forcing oneself to present the key concepts of the course in different styles
- If possible, sectioning classes to match learning styles between teachers and students
- Writing course material in a way that it appeals to different styles
- Allowing different required texts
- Identifying the learning styles of colleagues and recruiting their help in the creation of exams, weekly assignments, and the review of course texts
- Having learning-style ombudspersons in the class to help the professor prepare and assess class material
- During assessment, providing flexibility in exam questions
- Whenever possible, working with smaller groups and using co-operative learning (with group membership influenced by knowledge of students' learning styles)
- Individualizing teaching
- Individualizing testing
- Using the Keller "Proctorial System of Instruction" (PSI) plan.\textsuperscript{13}

To develop students' skill and flexibility in appreciating differences, Woods additionally recommends that we

- Plan activities to explicitly help develop those elements of style that are less robust and create learning environments to promote a target style
- Use small-group "self-directed learning" (SDL) or "problem-based learning" (PBL) with smaller (5 or 6) groups of students.

CONFLICTS BETWEEN LEARNING AND TEACHING STYLES

Junior professors might feel tempted to try some of the ideas suggested by Woods right away and to make changes in their teaching styles without full consideration. Although it is true that favoring one's own learning style by teaching in that style could be detrimental to students with different styles, it is also possible to create conflict with a higher proportion of students if they are not properly informed and involved in the change process.

There are several cases reported in the literature where conflict arose when changes were made to the instructor's teaching style. Saunders\textsuperscript{14} noted the case of reluctant behavior of some participants in role-play simulations. Anderson and Adams\textsuperscript{15} report conflict when students experience teaching styles that do not match their expectations. Miller, et al.,\textsuperscript{16} mention some of the disadvantages of active learning, such as poor structure or lack of structure. The dynamics of interpersonal relationships in co-operative learning groups and lack of individual responsibility on the part of group members are potential sources of conflict, even in carefully structured groups. Woods\textsuperscript{17} explains the problems (and solutions) encountered when incorporating PBL components (two courses) into the otherwise traditional chemical engineering program at McMaster University. In the paper he mentions nine issues of concern; one of them is gaining student acceptance.

A common remedy to eliminate or attenuate the conflict is to clearly inform the students of the objectives and benefits of the new approaches and to explain how they can manage conflict—prior to making the changes. In some cases it is important to previously train the students on necessary skills, such as problem-solving, interpersonal and group behavior, and learning approaches.\textsuperscript{18} Some students may be so reluctant to change that the use of different teaching styles and even different (yet known) assessment procedures may be needed.

EXPERTS' RECOMMENDATIONS FOR STUDENT LEARNING IMPROVEMENT

There are many things that can be done to accommodate differences in learning styles, levels of motivation, levels of intellectual development, and judgment modes among students. One approach is to try to follow the "seven principles" for good practice in undergraduate education:\textsuperscript{17}

- Encourage contact between students and faculty
- Develop reciprocity and cooperation among students
- Use active learning techniques
- Give prompt feedback
- Emphasize time on task
- Communicate high expectations
- Respect diverse talents and ways of learning

Wankat\textsuperscript{19} proposed "ten learning principles." The first six of them coincide with the previous principles, and the remaining four are:

- Develop a structured hierarchy of content and guide the learner
- Develop images and use visual modes of learning
- Challenge the students
- If possible, separate teaching and evaluations

Similarly, Bird\textsuperscript{10} also proposed "seven rules" for teaching:

- Do not show off
Felder and Silverman\textsuperscript{[9]} proposed several teaching techniques to address all learning styles. They include:

- **Motivating learning**
- **Providing a balance of concrete information and abstract concepts**
- **Balancing the material that emphasizes practical problem-solving methods with material that emphasizes fundamental understanding**
- **Providing explicit illustrations of intuitive and sensing patterns**
- **Following the scientific method in presenting theoretical material**
- **Using graphical material (pictures, plots, figures) before, during, and after the presentation of verbal material**
- **Using computer-assisted instruction**
- **Providing (short) active intervals during lectures**
- **Giving the students the option of cooperating on homework assignments to the greatest possible extent**
- **Applauding consistent effort**
- **Talking to students about learning styles**

The comfort level of feelers (in the Jungian typology) in technical courses can be raised by (a) bringing out the social relevance of the course material, (b) addressing some non-technical topics, and (c) using student-centered instructional approaches such as cooperative learning.\textsuperscript{[11]}

To promote a deep approach to learning, the following conditions should be present:\textsuperscript{[11]} student-perceived relevance of the subject matter; clearly stated instructional objectives, practice, and feedback; appropriate tests; reasonable workload; and choice over learning tasks.

To help the students move up the intellectual-development ladder, it is necessary to provide an appropriate balance of challenge and support, occasionally posing problems one or two levels above the student's current position. Instructors should assign open-ended, real-world problems throughout the curriculum, but should not make course grades heavily dependent on them. Providing feedback on performance with these types of problems is very important.\textsuperscript{[12]}

Felder, \textit{et al.},\textsuperscript{[20,21]} and Stice, \textit{et al.},\textsuperscript{[22]} have prepared a comprehensive study of teaching methods that promote learning and how to train teachers to apply those methods. The emphasis is on engineering courses, but most of the ideas are also applicable to other disciplines.

THOUGHTS ON WHAT TO DO TO IMPROVE STUDENT LEARNING

A junior professor might be overwhelmed by the amount of information cited in this paper for improving student learning by accounting for personal preference and implementing changes in their style of teaching. Even some experts on education recommend that junior professors in research-intensive institutions give priority to getting started with their research projects and obtaining funding; that they start modestly in their first teaching efforts, trying to get as much help as possible from senior professors when it comes to course design and material.\textsuperscript{[23]}

But what about those students in our classes during our first few years in academia? Is it okay to "lose" some of them during this early period of learning to teach? The answers to these questions should be answered by the new professors themselves. My first-year-as-a-professor answers are provided in the following paragraphs.

I envision teaching as a continuous attempt to promote students' growth, both intellectual and personal, by using optimal mixtures of the three components in play: the students themselves, the teacher (myself), and the subject discipline or course topic.

As to the first ingredient of the learning mixture—the students— there are several aspects that I try to keep in mind. The first is that students are human beings, and as such they deserve respect and consideration. The second important aspect is to recognize that students have different learning styles, attitudes, and motivations for learning. To get the best out of them (to be used in the "learning mixture"), it is necessary to motivate them (to an appropriate level), and to be able to adapt my teaching style to their learning styles, or to convince them of the convenience of being exposed to learning styles not initially compatible with theirs. Whenever possible, I try to allow my students to negotiate learning objectives and the assessment procedure.

The second ingredient in the mixture is the teacher—myself. Although most of my professional life has been focused on industrial engineering practice and applied research in polymer reaction engineering, I have always considered teaching as a noble and important activity. Much of what I am today was inspired by former teachers of mine and my parents. My love of mathematics, chemistry, and physics (key components in chemical engineering) was triggered with the help (and promoted by the example and teaching styles) of several excellent professors. Many of my teaching strategies were stolen from those teachers.

Some of the positive early aspects of my teaching style have been my respect for students (as a student, I was turned off by those who made students feel less intelligent, mature, or trained) and responsibility in my activities. As a teaching assistant at McMaster University, I always tried to fully
understand the material before a tutorial took place or when talking to students (most of the time I tried the solutions to assignments and exams myself, even when the solutions were available from the instructor). When I did not know the answer to a student’s question, I tried to find the answer and get back to the student as soon as I could. Whenever possible, I tried to design assignments that were connected to actual problems and situations that the students would face in their professional lives.

**Teaching is sufficiently important that we need to continuously refine it through a systematic and scholarly approach. That is the very least our students and our society deserve.**

Despite the fact that I followed the example of inspiring teachers in my early teaching experiences, I discovered that I was not as effective as I had wished to be. Being somewhat introverted and a “feeler” (in the Jungian typology), I realized that my teaching style was biased toward students with learning styles similar to mine. I did not use many group activities, my lecture material was abstract (mostly text, equations, and diagrams), and I used to speak softly. I knew something was not working the way I wanted it to. In this area, I received some valuable help from a credit course I decided to take while I was a graduate student (titled “Principles and Practice of University Teaching”).

The last ingredient in my teaching mixture is the course subject. If I want to teach something, I should understand it deeply and I should like it. I should be able to make it appealing and interesting to the students. I should be able to make the students understand why it is worth studying the discipline. To that end, I spent three years as a practitioner in order to garner first-hand experience in an actual work environment. To help my understanding of the area, I enrolled in graduate school where I obtained my MEng and PhD degrees. Throughout this time, I detected areas of opportunity for research and technological improvement and learned many things that I would like to share with students. I may even be able to help some individuals to find and exploit (or reinforce) their potential as professionals in this area.

In short, a young professor can improve student learning by liking to teach, establishing interesting and novel research lines, providing multiple real-life applications of topics taught in the course, taking advantage of the instructional development courses and facilities where and when available, and never ceasing to learn.

**CLOSING REFLECTIONS**

After two years of research and teaching experience as Associate Professor of Chemical Engineering, I can add some additional thoughts on the subject. It is not easy to be a “quick starter,” even if one tries to follow Brent and Felder’s advice on how to become one, or even if one reads what Felder wished he had been told.

I still made mistakes or inadequate choices during my first two years as a professor. In my first semester I offered a graduate course with “cutting edge” content and found I had to spend an average of six hours of preparation time per lecture hour (in the second semester I reduced that to a two-hour preparation per lecture hour, but was responsible for three courses). I put too much emphasis on the course content at the cost of little active student participation. As a thesis supervisor I gave too much freedom to my undergraduate and graduate students (I myself was the independent type who did not like my supervisors over me all the time) until I realized that most of them liked and needed closer supervision. I did not start manuscript writing early, so I had to spend several weeks of twelve to fifteen working hours in order to reach my own research goals during my first year as a professor.

Not everything could be classified as a “failure,” however. I also implemented some good ideas from the experts. I tried to incorporate much of my own research into my course materials; I started several collaboration projects with experienced researchers from industry; I asked colleagues to read and provide the toughest critique to my research proposals (so far, funding has been granted in all cases); I applied for course load reduction (standard optional procedure for the first two years of new faculty) in order to concentrate on research funding activities, etc.

In order to motivate students, the teacher does not necessarily have to be easy-going and charismatic (although it helps). Even introverted or absent-minded teachers can motivate students. In my courses I try to motivate the students in a number of different ways. For instance, as mentioned before, I use my research projects to provide examples of material covered in the course. This helps make matters more interesting and, at the same time, it helps attract students to my research projects. Sometimes there may be topics in the course that I do not feel at ease explaining (in advanced or graduate courses, for example)—in those situations, in addition to spending time reading and updating my knowledge, I try to invite other professors or respected industry researchers to give short lectures within the course. Students usually respond positively to these special lectures.

For one month during this school year I had a distinguished professor from Canada who participated in some of my courses and co-supervised some of my graduate students. They already know some of his work since I use it in my courses, and knowing he would be here had a positive
effect on my undergraduate and graduate students. They waited anxiously for his visit and felt they would learn something new and useful while he was here, which they indeed did. I am also arranging the visit of another well-known and well-respected Canadian professor next year who will co-chair with me the organization of a microsymposium within a major conference in my field.

My students, both undergraduate and graduate, are aware of my efforts to establish a research group. In a department where the average age of the professors is over 45, I find that some of the undergraduate students are eager to get involved in projects significantly different from the more traditional ones. Graduate students are more reluctant to change, though, and they usually prefer to work for senior professors. Nonetheless, they also acquire a high degree of motivation from courses where content is related to research as much as possible. Innovation and change gets students’ attention and encourages them to go beyond the contents of textbooks.

In other words, young professors can concentrate on setting up their research programs (what counts for promotions and stimuli in our academic world) and still be able to promote learning in their students by sharing with them the enthusiasm for this activity. Students who get involved with actual research projects in their courses develop a higher degree of motivation than students who just follow the book.

Students are individuals, and as such they have different learning styles, motivations, and expectations for learning. It is very important that when implementing “non-traditional” teaching methods in their courses, professors let their students know the objectives and the value of the new teaching approaches. It helps to stress the usefulness of these approaches. There may be students who remain reluctant to accept them, even after the purposes and benefits of non-traditional techniques have been explained. The instructor should be prepared to use alternate teaching styles or have alternate assessment procedures (known to the student).

Students are a precious resource that should not be squandered through ineffective teaching. Teaching is sufficiently important that we need to continuously refine it through a systematic and scholarly approach. That is the very least our students and our society deserve.

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THE PITZER-LEE-KESLER-TEJA (PLKT) STRATEGY
And Its Implementation by Meta-Computing Software

WILLIAM R. SMITH
University of Guelph • Guelph, Ontario, Canada N1G 2W1
MARTIN LÍSAL
Academy of Sciences • 165 02 Prague 6, Czech Republic
RONALD W. MISSEN
University of Toronto • Toronto, Ontario, Canada M5S 3E5

One way of using an equation of state (EOS) for pure fluids is to determine the EOS parameters by fitting them to experimental data for each individual fluid. Instead of a particular parameter set for each fluid, in a variant of this approach, an EOS is extended to broad classes of fluids by expressing at least one of the parameters in terms of critical properties, $P_c$ and $T_c$, and at least one additional parameter such as the acentric factor, $\omega$. The resulting generalized form of EOS, while less accurate for each individual fluid, is intended to provide a compact and reasonably accurate representation of the volumetric (and thermodynamic) properties of the entire class of fluids.

An important aspect of chemical engineering education is the study of this strategy of EOS construction and generalization, and its extension to fluid mixtures. A recent example of this strategy for pure polar and nonpolar fluids and their mixtures is described by Platzner and Maurer. A different and less common way of using an EOS for classes of fluids is to follow an approach originally proposed by Pitzer. It uses parameter sets corresponding to accurate representations of the behavior of selected reference fluids, and then approximates the properties of a class of fluids by incorporating an additional parameter such as $\omega$ in the form of corrections to the principle of corresponding states, in terms of an expression for $z(P', T')$ (where $T'_r = T'/T_c$ is the reduced temperature and $P'_r = P/P_c$ is the reduced pressure).

In this article, we explore the general basis for, and the utility of, this latter approach, which we believe has been insufficiently exploited in the pedagogical literature.

The correlation of Lee and Kesler for volumetric and thermodynamic properties of normal fluids, based on the acentric factor ($\omega$) of Pitzer, et al., is the most favored three-parameter corresponding states correlation (Smith, et al., p. 88). In spite of this accolade, almost all introductory thermodynamics books either ignore it or deal only with its implementation in graphical or tabular form.

Such pedagogical treatments of the correlation for the most part ignore the underlying basis, thus obscuring its possible extension to other classes of fluids, and by default its dependence on a particular representation of $PVT$ behavior. Such treatments also disregard the emphasis placed by Lee and Kesler on an analytical implementation in a form convenient for computer use. The graphical form is useful for a qualitative representation of the behavior of pure fluids,
but both tables and charts are inadequate for the best quantitative results. The extension of the PLK strategy by Teja, et al.,[9-13] (PLKT strategy), applicable to broader families of fluids, is not discussed at all in introductory texts.

The somewhat complex computer implementation necessary at the time of its original development has probably led to emphasis on the use of graphs and tables in teaching the PLK approach. But current computer implementation technology has advanced considerably beyond what was available twenty-five years ago. Implementations are now available in the form referred to by Edgar[44] as “meta-computing” software, involving the use of packages such as Maple,[15] Mathematica,[16] Mathcad,[17] and MATLAB.[18]

We agree with Sandler[19,20] that this type of software is especially useful in a pedagogical setting, since in addition to allowing the treatment of problems previously considered too complex at the undergraduate level, it “can let the student concentrate on the subject matter at hand . . . , rather than being distracted by computational methods, algorithms, and programming languages.”[20] This type of software is becoming increasingly accessible to engineering undergraduates and lends itself to efficient implementation of the PLK and the PLKT approaches.

Our purpose in this paper is two-fold:

1) To describe and emphasize the pedagogical importance of the PLKT strategy, both as a setting for understanding the essential basis of the PLK strategy for normal fluids and for extending it to other classes of fluids.

2) To describe an efficient analytical implementation of the PLKT strategy using meta-computing software.

We first describe the Pitzer-Lee-Kesler-Teja (PLKT) strategy and give an example of its application to two families of non-normal fluids. This description points up the generic nature of the original PLK strategy so as to remove any dependence on a particular equation of state and choice of reference fluids. We then describe, with an example, its implementation using meta-computing software. Throughout, we focus on representation of the compressibility factor, \( z = PV/nRT \), for pure fluids, but the determination of thermodynamic properties follows from this, as outlined, for example, by Lee and Kesler.[3]

THE PLKT STRATEGY

In 1955, Pitzer, et al.,[4,5] added a third parameter, \( \omega \), to the two-parameter \((P_c, T_c)\) principle of corresponding states for determining the thermodynamic properties of “normal fluids.” This was based on the concepts of

1) “simple” fluids with spherically symmetric intermolecular potentials/shapes, and

2) “normal” fluids with moderate departures from simple-fluid behavior,

and expressed as a linear relation for \( z \) in terms of \( \omega \),

\[
z(P_T, \omega) = z(0)(P_T, T) + \omega z(1)(P_T, T)
\]

where \( P_0 = P/P_c \) and \( T_0 = T/T_c \) are the reduced pressure and temperature, respectively, and \( \omega \) is defined by

\[
\omega = -\log_{10} p_r(T_r = 0.7) - 1.000
\]

where \( p_r^* \) is the reduced vapor pressure \((=p^* /P_c)\) of the substance at \( T_r = 0.7 \). Since the analytical representation of \( z(0)(P_c, T_c) \) and \( z(1)(P_c, T_c) \) is not feasible, Pitzer, et al., provided tables of their values based on analysis of experimental data. Curl and Pitzer[21] provided a criterion for normal fluids based on surface tension.

In 1975, Lee and Kesler,[3] to improve the Pitzer results for fluids involved in hydrocarbon processing, developed an analytical implementation for \( z(P, T) \) using a modified Benedict-Webb-Rubin (BWR) equation of state (EOS)[22] to represent the behavior of two reference fluids that served to determine \( z(0) \) and \( z(1) \) in Eq. (1). Lee and Kesler[3] described a procedure to implement this strategy to obtain \( z \) for a hydrocarbon fluid of interest at a given \((P, T)\), and they provided tables and charts of values of \( z(0) \) and \( z(1) \) as functions of \((P_c, T_c)\). We call this the Pitzer-Lee-Kesler (PLK) strategy.

In the 1980s, Teja and co-workers[0-13] generalized the PLK approach in three ways. First, they considered it as a special case of interpolation/extrapolation involving \( z(P_c, T_c) \) using two arbitrary, but conveniently chosen, reference fluids, and thus extended its use to “families” of fluids other than normal fluids. Second, they allowed the reference fluids to be represented by any convenient EOS. Third, they extended their approach to mixtures and to other properties, including viscosity,[23-26] surface tension,[27] and thermal conductivity.[28] We call this the Pitzer-Lee-Kesler-Teja (PLKT) strategy. No extensive published calculations show the utility of this approach for pure non-normal fluids, perhaps because the primary focus of their work was on mixtures.[29]

The basis of the PLKT strategy is to recognize that the essential assumption underlying the Pitzer approach is that \( z(P_c, T_c) \) is represented as a linear function of the acentric factor (Eq. 1). To determine this linear relationship with \( \omega \), we may select, from a family of fluids, two appropriate reference fluids, \( r_1 \) and \( r_2 \) (according to some specified criterion), with corresponding acentric factors \( \omega(r_1) \) and \( \omega(r_2) \). The equation for the linear \( z(\omega) \) relation for any member of the family can be determined from the two points \((\omega(r_1), z(r_1))\) and \((\omega(r_2), z(r_2))\) as

\[
z(P_T, \omega) = z(0)(P_T, T) + \frac{z(r_2)(P_T, T) - z(r_1)(P_T, T)}{\omega(r_2) - \omega(r_1)}(\omega - \omega(r_1))
\]

Lee and Kesler used Eq. (3) for the family of normal fluids.
fluids, with the reference fluids \( r_1 \) and \( r_2 \) chosen as a simple fluid (\( \alpha^{(1)} = 0 \)) and (essentially) n-octane (\( \alpha^{(2)} = 0.3978 \)), respectively. Equation (3), however, allows the use of any two reference fluids within a family. The original PLK strategy was developed for normal fluids; the following example illustrates the appropriateness of Eq. (3) for two families of non-normal fluids.

**Example 1**

Consider:

(a) the family of halogenated hydrocarbon refrigerants, and

(b) the family of normal alkanols.

Investigate whether the PLKT strategy of Eq. (3) can be applied to these fluid families.

**Solution:**

(a) Figure 1 (similar to Figure 2 of Pitzer, et al.\(^5\)) shows values of \( z(P_r, T_r) \) for nine halogenated hydrocarbon refrigerants (ranging from \( C_1 \) to \( C_5 \)) as a function of \( \omega \) at four values of \( (P_r, T_r) \), together with the corresponding results for normal fluids. The \( z \) points for the refrigerants were calculated using the NIST REFPROP software package\(^\text{i3}\) the full lines are least-squares fits through these points and are for comparison only. The dotted lines for normal fluids were calculated using a quantitative numerical implementation of the PLKT strategy, as described in the next section. Figure 1 indicates that the linear relationship of Eq. (3) holds for the family of refrigerants and that it is somewhat different from that for normal fluids (the agreement of the results at \( T_r = 1.30 \) is coincidental).

(b) Figure 1 also shows values of \( z(P, T) \) for the normal alkanols from methanol (\( \text{CH}_3\text{OH} \)) to n-eicosanol (\( \text{C}_{20}\text{H}_{42} \)). Experimental data\(^\text{i3}\) were used for \( z_c \) (at \( P = T = 1 \)), and at the other state points \( z \) was calculated for the first five \( \text{n-alkanols}\) using the Patel-Teja EOS.\(^\text{i3}\) The full line at \( P = T = 1 \) is a least-squares fit through the points and is shown for comparison only. Away from \( T = 1 \), there is perhaps an insufficient number of family members to draw a conclusion (and the first member, methanol, is anomalous according to the particular EOS used). But the data at \( T = 1 \) indicate that the linear relationship of Eq. (3) likely holds for the family of \( \text{n-alkanols}\) and that it is also somewhat different from that for normal fluids.

Finally, we remark that another way to extend the PLK approach to non-normal fluids is to incorporate parameters in addition to \( \omega \). For example, if parameters \((\alpha, \xi)\) are used, \( z(P, T) \) may be fitted to the plane through three points corresponding to three reference systems

\[
\begin{bmatrix}
\left(z^{(1)}_0, \omega^{(1)}_0, \xi^{(1)}_0\right), \left(z^{(2)}_0, \omega^{(2)}_0, \xi^{(2)}_0\right), \left(z^{(3)}_0, \omega^{(3)}_0, \xi^{(3)}_0\right)
\end{bmatrix}
\]

and the analog of Eq. (3) is

\[
z = z_0 + a\left(\alpha - \alpha^{(0)}\right) + b\left(\xi - \xi^{(0)}\right)
\]

where \( a \) and \( b \) are determined from the three reference systems. Essentially, this approach has been considered by Wu and Stie1,\(^\text{i3}\) by Platzer and Maurer,\(^\text{i3}\) and by Rowley and co-workers,\(^\text{i3}\) who selected as reference systems two specific nonpolar fluids and either water or methanol as the third reference system. Platzer and Maurer\(^\text{i3}\) compared their implementation of this approach with the alternative approach of expressing the EOS parameters in terms of \( \omega \) and \( \xi \). This last approach is beyond the scope of this paper.

**IMPLEMENTATION OF PLKT STRATEGY USING META-COMPUTING SOFTWARE**

In the typical case when the reference fluid EOS is expressed in terms of \( \nu \) and \( T \), implementation of the PLKT strategy for calculating \( z \) or \( P \), given \((\nu, T)\), is an explicit calculation. In contrast, calculating \( z \) or \( \nu \) given \((P, T)\) involves an implicit calculation entailing the solution of certain nonlinear equations. The underlying structure of this

![Figure 1. Compressibility factor, \( z(P, T) \), as a function of acentric factor, \( \omega \), for a family of refrigerants (filled circles), some members of the family of \( \text{n-alkanols} \) (open circles and triangles), and the family of normal fluids (dotted lines). Where present, the full lines are linear fits to the data points and are shown for comparison only. The refrigerants, \( z \) was calculated using the NIST REFPROP software package,\(^\text{ii}\) for the \( \text{n-alkanols}\), at \( T = 1.00 \), experimental critical data were used\(^\text{ii}\) for \( \text{C}_1 \) to \( \text{C}_5 \); at other temperatures, \( z \) was calculated only for \( \text{C}_1 \) to \( \text{C}_5 \) using the Patel-Teja EOS\(^\text{ii}\) and values of parameters provided; for the normal fluids, the dotted line is the original PLK strategy.\(^\text{ii}\) The refrigerants on the graph (in order of their \( \omega \) values) are \( R_{13}, R_{21}, R_{22}, R_{23}, R_{215}, R_{1340}, R_{316}; \) the corresponding order for the \( \text{n-alkanols}\) is \( C_1, C_6, C_7, C_11, (C_5, C_8, C_9, C_{14}, C_{16}, C_{17}, C_{18}, C_{20}, C_9, C_{15} \) at \( T_r = 1 \), and \( C_1, C_5, C_4, C_3, C_2 \) at other temperatures.\(^\text{ii}\)
calculation is made transparent by the use of meta-computing software. We describe the approach in both cases and provide an example calculation for the latter situation.

When the EOS for the reference fluids is given explicitly in terms of \( v \) and \( T \), we write

\[
z = f(v, T; p)
\]

(5)

where \( p \) denotes a set of parameters that take on particular values for individual fluids. The particular EOS that Lee and Kesler used in the implementation of their approach\(^\text{[31]}\) is written in the form

\[
z = f(v, T; p)
\]

(6)

where \( v' \) is the ideal-gas reduced volume defined by

\[
v' = \frac{P_v v}{RT_c} = z_c v_r
\]

(7)

and \( v_r \) is the actual reduced volume, \( v / v_c \). Now

\[
z = \frac{P_v}{RT} = \frac{P_{v'}}{T_{v'}} = \frac{P_{v r'}}{T_r} = \frac{P_{v_c}}{T_r} z_c v_r
\]

(8)

Equation (8) shows that, in the use of an EOS to calculate \( z \) at a given \( (P, T) \), the set of reduced variables \( \{P, T, v_r\} \) is more appropriate than the set \( \{P, T, v_r\} \), since the former requires neither an assumption about the constancy of \( z \) nor a knowledge of \( v_r \). Since the usual form of an arbitrarily chosen EOS, Eq. (5), involves \( v, v \) must first be converted to \( v' \) to use the PLKT strategy in conjunction with it. This is a subtle point that is not apparent in the pedagogical literature; it affects the calculation of \( z \) both from a given \( (v, T) \) and from a given \( (P, T) \).

### Calculation of \( z(v, T) \) via Eq. (5)

To calculate \( z(v, T) \) for a substance with critical constants \( (P_c, T_c) \) and acentric factor \( \omega \), the following (explicit) equations are used when the EOS is expressed in terms of \( (v, T)(i.e., \text{ via Eq. } 5) \)

\[
\begin{align*}
  z^{(1)} &= f\left(\frac{RT_c}{P_c^{(1)}}, T_{v_r} T_{(1)}, p_{(1)}\right) \\
  z^{(2)} &= f\left(\frac{RT_c}{P_c^{(2)}}, T_{v_r} T_{(2)}, p_{(2)}\right)
\end{align*}
\]

(9, 10)

where \( v'_r \) and \( T_r \) are calculated using the properties of the fluid of interest. The value of \( z \) is then obtained from Eq. (3).

### Calculation of \( z(P, T) \) via Eq. (5)

To calculate \( z(P, T) \) when the EOS is expressed in terms of \( (v, T) \), Eq. (5), an implicit calculation must be performed involving the solution of nonlinear equations for the reference fluids as follows:

1. Calculate \( T_r \) and \( P_r \) using the properties of the fluid of interest.
2. Calculate \( z^{(1)} \) as the solution of the nonlinear equation

\[
z = f\left(\frac{RT_c^{(1)}}{P_c^{(1)}}, T_r, z; p_{(1)}\right)
\]

(11a)

4. Calculate \( z^{(2)} \) as the solution of the nonlinear equation

\[
z = f\left(\frac{RT_c^{(2)}}{P_c^{(2)}}, T_r, z; p_{(2)}\right)
\]

(11b)

5. Calculate \( z \) from Eq. (3).

### Calculation of \( z(v, T) \) and \( z(P, T) \) via Eq. (6)

When the EOS is expressed in terms of \( (v'_r, T_r) \) (as is the case for the Lee-Kesler EOS\(^\text{[31]}\)), Eqs. (9,10) and (11a,11b) are, respectively,

\[
\begin{align*}
  z^{(1)} &= f\left(v'_r, T_r; p_{(1)}\right) \\
  z^{(2)} &= f\left(v'_r, T_r; p_{(2)}\right)
\end{align*}
\]

(12, 13)

for \( z(v, T) \), and

\[
\begin{align*}
  z &= f\left(\frac{RT_c}{P_c^{(1)}}, T_r; p_{(1)}\right) \\
  z &= f\left(\frac{RT_c}{P_c^{(2)}}, T_r; p_{(2)}\right)
\end{align*}
\]

(14, 15)

for \( z(P, T) \).

The calculation procedure is illustrated in Figure 2 (next page), which shows a Maple\(^\text{[15]}\) script for calculating \( z(P, T) \) using the PLKT strategy in conjunction with an EOS expressed in terms of \( (v, T) \). To make the approach itself transparent, a simple technique is incorporated into the script to calculate only the largest value of \( z \); this suffices for the supercritical case, but for the subcritical case only the "vapor-like" root is found. It is left as a student exercise to modify the script to calculate the appropriate result in any given circumstances, which requires either a (somewhat complicated) calculation of the vapor pressure using Eq. (3), or use of the vapor pressure correlation of Lee and Kesler\(^\text{[3]}\).

Corresponding scripts for Mathematica\(^\text{[16]}\), Mathcad\(^\text{[17]}\), and MATLAB\(^\text{[18]}\) can be obtained from the web site at http://www.chemical-stoichiometry.net/PLKT/. Scripts for the calculation of \( z \) given an EOS expressed in terms of \( (v'_r, T_r) \) are also available at this location. Use of the Maple\(^\text{[15]}\) script is illustrated by the following example.

### Example 2

n-propanol (\( C_3 H_8 O \)) is to be stored in a 200-liter cylinder
at 230°C. What is the maximum amount (kg) that can occupy the cylinder as vapor? For n-propanol, Pc = 5170 kPa; Tc = 536.71 K; \( \omega = 0.628 \); M = 60.10; and \( p^*(230^\circ C) = 2996 \) kPa. (Data are from Yaws,\textsuperscript{334} except for the vapor pressure, which is from the DIPPR Student Chemical Database web site.\textsuperscript{343}) Use the PLKT strategy with ethanol (\( \omega_{(1)} = 0.637 \)) and n-pentanol (\( \omega_{(2)} = 0.594 \)) as reference fluids \( r_1 \) and \( r_2 \), respectively, and the Patel-Teja EOS\textsuperscript{35,36} in conjunction with Eq. (3). Values of the parameters \( p_{(1)}^{\omega} \), \( p_{(2)}^{\omega} \) are given by Patel and Teja.

Solution:

For the amount of vapor to be a maximum, the highest pressure is \( P = p^*(230^\circ C) = 2996 \) kPa. The amount is

\[
m = nM = \frac{p^* VM}{zRT}
\]

All quantities in Eq. (16) are known except \( z(p^*,T) \). Using the PLKT procedure described above and the Maple script shown in Figure 2, we obtain the values

\[
z = 0.6279 \quad m = 13.71 \text{ kg}
\]

(For comparison, direct use of the Patel-Teja EOS\textsuperscript{35,36} gives \( z = 0.6283 \) and \( m = 13.70 \) kg.)

CONCLUSIONS

1. We believe that it is important in teaching the PVT behavior of fluids to emphasize the general basis for the Pitzer-Lee-Kesler-Teja (PLKT) strategy as an

```maple
# PLKT strategy for z(Pr,Tr) using Patel-Teja EOS for n-alkanols
# Reference fluids are ethanol, n-pentanol
restart;R:=8.3145;
omega1:=0.637;Tc1:=516.25;Pc1:=6384000.;zeta1:=0.300;F1:=1.230395;
omega2:=0.594;Tc2:=586.15;Pc2:=3880000.;zeta2:=0.311;F2:=1.242855;
omega_b1:=fsolve(x^3+(2-3*zeta1)*x^2+3*x-zeta1^3,x,0..10.);
omega_b2:=fsolve(x^3+(2-3*zeta2)*x^2+3*x-zeta2^3,x,0..10.);
omega_a1:=3*zeta1+3*(1-2*zeta1)*omega_b1+omega_b1^2-1-3*zeta1;
omega_a2:=3*zeta2+3*(1-2*zeta2)*omega_b2+omega_b2^2-1-3*zeta2;
omega_c1:=1-3*zeta1;omega_c2:=1-3*zeta2;
alpa:=(F,Tr)->(1+F*(1-Tr-(0.5)))*2;
a1:=omega_a1*R*2*Tc1^2/Pc1;a2:=omega_a2*R*2*Tc2^2/Pc2;
b1:=omega_b1*R*Tc1/Pc1;b2:=omega_b2*R*Tc2/Pc2;
c1:=omega_c1*R*Tc1/Pc1;c2:=omega_c2*R*Tc2/Pc2;
zPT:=(v,T,a,b,c)->(R*T/(v-b)-a/(v*(v+b)+c*(v-b)))*v/R/T;

# Example 2 re n-propanol
omega:=0.628;Pc:=5170000.;Tc:=536.71;
T:=230.+273.15;P:=2996000.;Tr:=T/Tc;Pr:=P/Pc;
if Tr>1 then
  z1:=fsolve(xx=zPT(xx*R*T1/P1,T1,a1*alpha(F1,Tr),b1,c1),xx,0..10);
  z2:=fsolve(xx=zPT(xx*R*T2/P2,T2,a2*alpha(F2,Tr),b2,c2),xx,0..10);
else
  x:=5.;
  while x-zPT(x*R*T1/P1,T1,a1*alpha(F1,Tr),b1,c1)> 0 do x:=x-0.01 end do;
  z1:=fsolve(zz=zPT(zz*R*T1/P1,T1,a1*alpha(F1,Tr),b1,c1),zz..x+.01);
  x:=5.;
  while x-zPT(x*R*T2/P2,T2,a2*alpha(F2,Tr),b2,c2)> 0 do x:=x-0.01 end do;
  z2:=fsolve(zz=zPT(zz*R*T2/P2,T2,a2*alpha(F2,Tr),b2,c2),zz..x+.01);
end if;
z:=zl+(omega-omega1)/(omega2-omega1)*(z2-z1);
m:=P*0.2*60.1/(z*RT);
```

Figure 2. MAPLE\textsuperscript{45} script for Example 2. This and scripts in Mathematica,\textsuperscript{46} Mathcad,\textsuperscript{17} and MATLAB\textsuperscript{48} can be obtained from the web site at http://www.chemical-stoichiometry.net/PLKT/PLKT/
implementation of the three-parameter principle of corresponding states. This makes clear the underlying basis for the Pitzer corresponding-states approach and makes extensions more self-evident; we have provided an example of possible extensions to the family of halogenated hydrocarbon refrigerants and to the family of n-alkanols.

2. We believe that it is important pedagogically to emphasize the quantitative (analytical) implementation of the PLKT strategy rather than the use of tables and charts, although the latter are useful qualitatively. This quantitative implementation is easily carried out using meta-computing software.

3. We have shown an implementation for a three-parameter corresponding states prediction of the compressibility factor to calculate \( z(P,T) \) when the EOS is given in the form \( z(v,T) \) using meta-computing software. We have illustrated this with an example using MAPLE\textsuperscript{15},\textsuperscript{16} files for Mathematica,\textsuperscript{17} and MATLAB\textsuperscript{18} can be obtained from the web site at http://www.chemical-stoichiometry.net/PLKT/. Also contained on this web site are four corresponding files for calculating \( z(P,T) \) when the EOS is given in the form \( z(v^*,T) \).

ACKNOWLEDGMENTS

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REFERENCES

14. MAPLE is a registered trademark of Waterloo Maple, Inc.
15. Mathematica is a registered trademark of Wolfram Research, Inc.
16. Mathcad is a registered trademark of MathSoft, Inc.
17. Mathcad is a registered trademark of MathSoft, Inc.
18. MATLAB is a registered trademark of The Mathworks, Inc.
34. http://diippr.byu.edu/students/.

Ben-Gurion University of the Negev, Israel

The Department of Chemical Engineering of Ben-Gurion University of the Negev invites applications for tenure-track faculty positions to start September, 2001. Duties consist of teaching at the undergraduate and graduate levels and conducting innovative research. Applicants should have a PhD degree in engineering or sciences (a degree in chemical engineering will be considered an advantage) and should have demonstrated his/her potential for excellence in teaching and research.

The Department of Chemical Engineering has four tracks of specialization at the undergraduate level:

- *Advanced materials (microelectronics, catalysis, and polymers)*
- *Biochemical engineering*
- *Chemical process engineering*
- *Computer applications in chemical engineering*

It is expected that the selected candidate will contribute to teaching in some of the specialization tracks and will interact with faculty members.

Applications should be addressed to:

Prof. Jose C. Merchuk, Head
Department of Chemical Engineering
Ben-Gurion University of the Negav
PO Box 653
Beer Sheva 84145, Israel

Winter 2001
The Chemical Engineering Program at the University of California, San Diego, has successfully operated a unique Chemical Engineering Process Laboratory since the early 1980s[1] that is taught at the senior level over two quarters for a class size under forty. The emphasis of the laboratory is to develop skills in planning, designing, and building an experimental apparatus, performance of experimental work, analysis of data, and making proper interpretation and decisions. Learning how to make effective oral technical presentations and developing report-writing skills are also integral parts of the course.

The projects of this course range from the more traditional areas of kinetics and transport phenomena to applications in microelectronics, environmental engineering, and biotechnology. The uniqueness of this process laboratory class is its attempt to emulate industrial process development projects with one in-depth project rather than rotating through a set of unit operation equipment each quarter for each small group of students.

CHEMICAL ENGINEERING PROCESS LABORATORY

Although the philosophy of the class has remained the same since its inception,[1] some changes have been made in the details of its execution. For each ten-week project, a proposal and a safety memorandum must be written. In the project proposal, the proposed plans and methods form the main body of the proposal and the background section must have a critical review of at least five to six pertinent research articles. A proposal should clearly identify the objectives of the project, demonstrate an understanding of the relevant literature, establish the significance of the proposed work, and outline the approach.

The safety memorandum should be a summary of pertinent information from the MSDS of any chemicals that may be used in the specific project, should contain specific safety precautions and lab procedures, and should address the issue of waste minimization. With a better appreciation of the importance of planning, the students are required for the second quarter to prepare and use a project schedule (a so-called Gantt) chart. During each quarter, students must demonstrate experimental design on their new project and scale-up calculations as specified by their project director.

We have recently introduced a group rotation project (e.g., a cooling-tower or heat-exchanger project) that is ongoing each quarter and that involves the whole class. The objective of the project is to learn group-to-group communication to achieve a common goal by having each group work on the project for one week. The students analyze their data and then write a memo that summarizes their progress and advises the next group of the new tasks to be accomplished. To communicate the success of the laboratory projects, the final
This laboratory course has been an excellent vehicle for teaching and demonstrating electrochemical engineering principles.

ELECTROCHEMICAL ENGINEERING

This laboratory course has been an excellent vehicle for teaching and demonstrating electrochemical engineering principles. The applications of electrochemistry are diverse and the projects in the laboratory have spanned the gamut from energy conversion (fuel cell) to electroplating to environmental engineering. The electrochemical engineering projects typically involve thermodynamics, kinetics, transport processes (diffusion, convection, and electromigration), reactor design, and scale up.

The students readily determined, after reviewing the electrochemistry from their physical chemistry class, that electrochemical processes can be analyzed using chemical engineering principles. The main difference is the addition of the effects of a potential gradient. But for the experiments and analysis of data, the ability to control and measure voltage or current can often be an advantage as it gives direct information about the process. The minimum voltage may be related to $\Delta G$ of the reaction. The current density may be proportional to the rate of heterogeneous reaction. The limiting current density can be related to the mass transfer rate. The design of an electrochemical reactor is often analogous to a heterogeneous reactor in which the surface area to volume needs to be maximized. Attention must be given to potential and current distributions, however.

Table 1 (next page) lists the project statements that have been assigned in the class over the past decade. Note that the statements are all the students receive, which emphasizes the open-ended problem at hand.

The main piece of necessary laboratory equipment is a potentiostat to control voltage and measure current (average cost is about $12,000). Also, reference electrodes are used in most experiments. The most expensive materials were ion exchange-membranes or dimensionally stable electrodes, which were used in as small amounts as possible when required.

A generic electrochemical reactor that could be used repeatedly was a project one year and it has been used by other groups for many experiments. Note that four of the projects (6 through 9) are of an environmental engineering nature, which is of great interest to the students. There is the added benefit to the professor in actually observing how these various processes work.

It is also possible to incorporate the experiments given in Table 1 into a more traditional unit operations laboratory with a focus on kinetics or mass transport aspects. The experimental stations, such as the reciprocating-paddle system to be discussed, were built in our shop with inexpensive materials such as plexiglass and used simple pumps and motors (at a total cost of less than $200).

EXAMPLE EXPERIMENT

To illustrate the development of one of the lab projects, a study of copper electrodeposition with a reciprocating-paddle system will be used as an example to show how the principles of electrochemical engineering were explored by the students in a design context. It was one of the most successful projects; this very motivated and industrious group wrote a journal note\textsuperscript{23} from the results of their project.

The group of students was given the problem statement (#3, Table 1), and they proceeded to design and build (with help from a technician) their experimental apparatus based on information from a patent\textsuperscript{31} in which a reciprocating paddle cell had been used to deposit magnetic alloy films. A schematic of their experimental apparatus is shown in Figure 1.

The plating cell was a plexiglass tank to be filled with...
### TABLE 1
Project and Scale-Up Design Problem Statements

<table>
<thead>
<tr>
<th>Project Statement</th>
<th>Scale-Up Design Problem</th>
</tr>
</thead>
</table>
| **1) Methanol-air fuel cell**  
Fuel cells can be useful power sources (particularly for operation in remote areas) due to their high energy density and quiet operation. However, in a methanol-air fuel cell, methanol is soluble in the aqueous electrolyte and can diffuse to the cathode where it can oxidize. Our client is interested in an application of a methanol-air fuel cell, but is aware that there are problems. The problem of diffusion of methanol to the cathode is an important problem to our client that needs to be investigated. Please develop an experimental plan and design an appropriate apparatus to conduct your study. | **1a)** It has been proposed to use a methanol fuel cell system remotely in small cabins for weekend recreational power usage. Please design a fuel-cell system for this purpose. Discuss the power requirements and costs.  
**1b)** Our client was very pleased with the design of the batch apparatus for the methanol-air fuel cell study. However, for continuous use, our client would like the fuel cell to be designed as a continuously stirred tank reactor with recycle of the electrolyte.  
**1c)** Our client would like a design of a cross-flow array assembly of methanol-air fuel cells to supply back-up power to a personal computer for eight hours. Base this design on the results of your experimental study of a methanol-air fuel cell. |
| **2) Electrolytic gas evolution**  
In conventional bioreactors, oxygen is provided to the cells by bubbling air through the growth medium. This method has several disadvantages, however, including nonuniform distribution of oxygen, destruction of fragile cells from induced shear, and risk of contamination. In past studies of mass transfer of oxygen in both air-lift and bubble-column reactors, our development engineers have determined that achievement of an adequate gas-liquid mass transfer coefficient was not possible. However, a novel electrochemical aeration system has been suggested to enhance mass transfer by evolving oxygen electrolytically as finely dispersed bubbles. Please develop an experimental plan and design a system to conduct your investigation. | Our client would like a design of a 10-liter aerobic bioreactor to produce penicillin using electrolytically evolved oxygen and air sparging in a bubble column. Compare the costs associated with using electrolysis and compressed oxygen. |
| **3a)** An electroplating process is being used by our client to produce thin metal films for magnetic recording heads. Our client would like us to investigate the use of a reciprocating paddle as a means of electrolyte agitation. Please develop an experimental plan and design an appropriate apparatus to conduct your investigation.  
**3b)** Our client was satisfied with the investigation of the use of a reciprocating paddle as a means of electrolyte agitation for copper deposition which was initiated during the last quarter. However, we have been informed that organic agents are routinely added to the plating baths to enhance the quality of the electrodeposition. We need to understand if these additives affect the mass transfer and the kinetics of deposition. Please develop an experimental plan to conduct your investigation. | **3a)** Our client would like a design of a copper-plating system using a reciprocating paddle means of electrolyte agitation to plate multilayer circuit board through-holes.  
**3b)** Our client would like a design of a system for uniform electroplating of a 1-µm film of copper on a 1 m x 1 m device. Please design a commercial-scale electroplating process that uses the reciprocating paddle for agitation. Also include a procedure for operating the electroplating system that you design. |
| **4) Electroplating of through-holes**  
Plated through-holes provide electrical connections between the different layers of printed circuit boards. However, the trend in the development of multilayer printed circuit boards is towards more layers and narrower diameter through-holes. Therefore, as through-hole aspect ratio (length-to-diameter) increases, uniform electrodeposition of a through-hole becomes very challenging. We wish to study the electrodeposition of copper in a through-hole in order to characterize the important process variables that affect plating uniformity. Please develop an experimental plan and design an appropriate apparatus to conduct your investigation. | Our client would like a design of a copper-plating system to plate the through-holes of a multilayer circuit board. The 0.381-cm (150 mils) thick circuit board has an array of 100 through-holes, each with a radius of 0.064 cm (25 mils) with a hole-to-hole distance of 0.254 cm. The minimum thickness of 0.0025 cm (1 mil) of copper is required at the center of each through-hole. In your design, consider agitation of the electrolyte solution by pumping the solution. Estimate the cost of power required for electroplating and pumping of the solution. |
| **5) Electroforming process**  
An electroforming process is being used by our client in making orifice plates for their thermal ink jet printer. Our client wants a study of an electroforming process to better understand the effects of various important system parameters, such as anode-cathode orientation, applied potential drop, and electrolyte concentration. Please develop an experimental plan and design an appropriate apparatus to conduct your investigation. | Our client was very impressed with the design of the parallel-plate electroplating process considering the effects of the primary current distribution. However, our client would like to consider a system for uniform electroplating with flow through parallel plate electrodes. Please design a commercial scale electroplating process for a flowing electrolyte. |

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Continued on next page
about 10 liters of the plating solution. A 1-cm² copper cathode was mounted in the center of a platform raised above the tank floor. The raised platform was added to allow fluid displaced by the paddle to flow underneath it to minimize waves induced from the tank walls. Flow visualization was performed by the students with this system.

A simple rectangular block fixed on a tracking system was used as the paddle driven by a motor in a reciprocating motion at various velocities and heights above the cathode surface. A copper anode was placed parallel above the cathode support. The anode area was about 250 times that of the cathode, to allow it to function as a relatively unpolarized reference electrode as well as a counter electrode. The solution was either a binary electrolyte 0.05M CuSO₄ or a supporting electrolyte solution of 0.05M CuSO₄ and 1.7M H₂SO₄. One of the students mentioned that this project kept him in style with "acid-washed" jeans, which were very popular at that time.

The quality of the 1-µm thick film was determined by using microscopy and profilometry. Applied potential and current were controlled and measured, respectively, by a potentiostat, connected by copper-wire leads to the electrodes.

Before building the apparatus, the first step for this project was to learn about the thermodynamics, kinetic, and mass transport of electrochemical systems. Often, a comfortable place for a student (or a faculty member) to begin is the chapter on electrochemistry in a physical chemistry textbook.

There are also several good basic books on electrochemistry and electrochemical engineering (see Table 2) appropriate for the novice. Extra time has not been needed to lecture to the students on electrochemistry; this information is garnered through specific technical problems the students encountered either in reading literature or in conducting an experiment.

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**Table 1, continued.**

| 6) Packed-bed electrode system | 6a) A typical average discharge rate from a plating shop is 50,000 gal/day. Based on your bench-scale packed-bed electrode system, design a waste-treatment system to accommodate this flow rate that meets the EPA discharge standards.

6b) ELTECH Systems Corporation (Sugarland, TX) sells a heavy-metal recovery electrochemical cell with an extended surface area provided by use of a "reticulated" metal sponge cathode. The cathode presents an actual surface area almost 15 times its geometrical area. The cathodes are used in a cell as porous flow-through electrodes that are placed in series with flow-through anodes. The typical cell operating conditions for a copper sulfate stream are a feedrate of 3 gal/min with an inlet concentration of 250 ppm and an outlet concentration of 5 ppm. The average rate of removal is 0.36 lb/hr. The process conditions are a cell current of 200 amps and a voltage between 1.5 and 5.5 V. Please design a packed-bed cathode cell (or a series of cells) that can compete with the ELTECH system. Discuss the power requirements.

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| 7) Electrokinetic soil remediation | 7a) Based on your bench-scale experimental results and information from the literature, design a scaled-up system to treat phenol at 200 ppm from 1000 gal/day of wastewater to U.S. effluent water standards. Please consult with the other two groups (Fenton’s Regent Group, UV Oxidation Group) in order for us to make a "fair" comparison of these technologies.

7b) Design a cell (or a series of cells) with the ELTECH-type system (see 6b) with an inlet concentration of 150 ppm of phenol. Discuss the power requirements and costs.

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| 8) Electrochemical oxidation of organics | 8a) Our company has been asked to evaluate using an electrochemical oxidation system for the treatment of organic constituents in a wastewater stream. A recent article is attached that briefly reviews both indirect and direct oxidation processes. Your group needs to determine the appropriate technology, a chemical system to study, and a plan of development for a wastewater treatment system.

8b) Design a cell (or a series of cells) with the ELTECH-type system (see 6b) with an inlet concentration of 150 ppm of phenol. Discuss the power requirements and costs.

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| 9) Electrochemical ion exchange | 9a) Our company has been asked to evaluate an electrochemical ion exchange system for the treatment of toxic metal ions in a wastewater stream. Your group needs to determine the appropriate technology, a chemical system to study, and a plan of development for a wastewater treatment system.

9b) Design an EIX cell (or a series of cells) that can compete with the ELTECH system (see 6b). Discuss the power requirements. Also, consider elution of the resin to recycle make-up stream to a plating operation that uses a concentration of 200 g/l CuSO₄.

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The important reactions that the students must consider are the electroplating of copper and hydrogen evolution at the cathode and the corrosion of copper at the anode. An explanation of the relationship between free energy change of reaction ($\Delta G$) to electrochemical potential through the Nernst equation and then use of a Pourbaix diagram (potential vs. pH) give a direct use of thermodynamics. The students readily determined and demonstrated the minimum potential required for electroplating of copper (and also in order to avoid hydrogen evolution).

By connecting the electrodes in a solution in a beaker (which is typically done first to understand the basics of anodic and cathodic reactions) and then in the actual plating apparatus, the student stepped (or ramped) the potential difference, $E$, and measured current, $i$ (to attain a polarization curve).

For this experiment, the applied potential was decreased in steps beyond the mass transfer limiting current plateau until a sharp increase in current was observed, indicating the dominance of $H_2$ evolution, as shown in Figure 2. The current efficiency of copper electrodeposition was determined by measuring the weight gain of a sample at limiting current over a specified period of time, using Faraday’s law. Therefore, the kinetics of copper plating and at very cathodic potentials, hydrogen evolution, were illustrated.

Due to the reciprocating motion of the paddle, the current transients at a set applied potential were periodic. Therefore, an average of the maximum and minimum current values at each applied potential difference associated with the reciprocating paddle motion was used in Figure 2.

The mass transfer limiting current plateau for copper electrodeposition is easily identifiable in Figure 2. The limiting current densities for the binary electrolyte were higher than the supporting electrolyte, as expected—indicating the influence of electrical migration on the transport of copper ions for the binary electrolytic solution. The effect of forced convection is also readily observable.

**Figure 2.** Polarization curve from copper deposition in 0.5 M CuSO$_4$ and 1.7M H$_2$SO$_4$ in a reciprocating paddle cell.

**Figure 3.** Mass transfer correlation.

**TABLE 2**

List of Recommended References

**For the Novice**
- Industrial Electrochemistry, 2nd ed., D. Fletcher, F.C. Walsh; Chapman & Hall (1990)

**For the More Advanced**
- Electrochemical Reactor Design, D.J. Pickett; Elsevier (1979)
logical survey of the copper deposit, showed that the paddle motion seemed to improve the deposition uniformity at the cathode edges parallel to the paddle motion.

The effect of thiourea on copper deposition was also studied. Thiourea ($SC(NH_2)_2$) is often added to plating solutions to refine the grain size and brighten the deposit. The addition of thiourea to the plating solutions did not influence the limiting current density for copper deposition, but did affect the surface kinetics and properties of the deposit.

CONCLUSIONS

During the two quarters of the design lab (10 weeks each), two groups of chemical engineering seniors designed, built, and operated a reciprocating-paddle electrochemical system. A correlation was determined to describe the mass transfer limited operation of an electroplating bath using this device in which binary and supporting electrolyte solutions exhibited the same power law correlation. This correlation would allow scaling the system for industrial applications.

To optimize deposition rate and uniformity, the highest paddle velocity (43 cm/s) and a paddle height of 1.0 cm above the cathode was recommended. Comparison of the deposition surfaces with and without agitation showed no loss of uniformity with agitation, while increasing the deposition rate by at least five times.

The other experiments listed in Table 1 followed a similar procedure, with varying degrees of success. The principles of chemical engineering and design were readily demonstrated in each of the experiments. A few students became interested in the specialization of electrochemical engineering and later they even took my graduate course on electrochemical engineering.

ACKNOWLEDGMENTS

The author acknowledges the contributions of colleagues, Professors Pao Chau and Richard Herz, who have also taught and improved this course over the years. The laboratory has been skillfully managed by Victor Gruol.

REFERENCES

Teaching methods involving only a lecture (or its variants) and a problem set format have several shortcomings. For example, they neither promote the creativity nor develop the independent thought processes that are desirable for a students' future endeavors in the "real world."

One of the strategies that has been widely discussed to partially offset the constraints of the lecture-problem set teaching method, is the use of open-ended problems. Such problems develop the important skill of divergent production in students. Most open-ended problems, however, are limited by the instructor; for example, the creativity aspect is limited to finding various solutions to a particular, instructor-assigned (and thereby, instructor-limited) problem.

There are usually several students who are inherently more creative than the experience-honed instructor, and such an exercise does not fulfill the academic passions of those students. Also, for many students the concept of rational choice, which is crucial to success in the real world of industry or research, is not well developed. For example, based on questions posed to first-year students taking material and energy balances, we found that only 4 to 5 students in an 80-student class are clear as to why they chose chemical engineering as their major. This probably happens because most students come from well-protected family environments into a reasonably well-protected campus environment for their undergraduate studies, and they accept established hierarchies or trends without considering their own individual strengths or affinities.

To address these issues, a Choose/Focus/Analyze (CFA) exercise was conceived and given to students taking the first-year Material and Energy Balances course and the second-year Engineering Thermodynamics course for the past four years. A similar exercise (with minor variations in exercise philosophy) was also given to students taking courses with limited depth, such as Elements of Chemical Engineering (to non-chemical engineering students) and Bioprocess Principles, over the same period. This article discusses the CFA exercise along with summaries of some student exercises that this instructor found interesting.

ASSIGNMENT

The following assignment was made during the discussion of the course-information material that was handed out to students on the first day of classes:

Problem Analysis: Students have to choose a problem of relevance to industry or any human endeavor and analyze it using the material and energy balance principles (or thermodynamics principles, for the thermodynamics course) learned in class. This is an open-ended problem that has been designed to improve the choice, focus, and analysis skills in students. The evaluation will be based on:

- Originality in approach 15%
- Focus level 15%
- Depth of analysis 20%
- Quality of work 20%
- Original contribution 20%
- Presentation (mainly communication) 10%

A concise report (in the format that you think would best communicate your work) submitted a week before the last day of classes will be evaluated strictly based on the criteria given above. It will help if the problem is chosen well in advance (within the first four
Each student had to perform the exercise individually, and it carried either a 15% or a 20% weightage toward the final grade.

To make students self-reliant, the instructor offered help only when
- The student decided to visit an industry. An introductory letter was provided in these cases, but the students were clearly informed that a letter alone would not guarantee their admission to the industry. The fact that more than 75 students over the past four years have managed to visit an industry for this exercise indicates their relevant abilities, either native or developed for this exercise.
- The student wanted to know if the problem was "too small" or "too large." The instructor would give his opinion on that aspect alone.

The instructor was readily available, however, to clarify the other aspects of the course, such as class material, concepts, and problem sets.

Students who thought of novel aspects to analyze were awarded high marks under the “originality in approach” heading, whereas the students who made good contributions, irrespective of whether the aspect was novel or not, were awarded high marks under the “original contribution” heading. Also, students who focused clearly on their task received high marks under the “focus level” heading, and students whose analysis had good depth scored high under the “depth of analysis” heading.

REPORT SAMPLES

Summaries of selected student exercises are presented in the following paragraphs. The report titles were those given by the students, with the student’s name and the course title denoted below.

**Fighting Alcoholism: A Chemical Aspect!**
_Gaurav Tayal_ (Material and Energy Balances)

This report demonstrated the use of material and energy balances to analyze a situation that is socially relevant. In his statement of motivation, Gaurav Tayal noted, “I have quite a few friends in my hostel [dorm] who can be classified as casual drinkers. What inspired me to undertake this exercise was the withdrawal symptoms that my friends suffer the next morning after drinking.” He also conducted a short survey that he did among his friends in the hostel who drink, which showed that almost all the participants wanted control over their state the morning after. He clearly identified (focused on) the following aims for this exercise:

- “What should be the maximum rate of intake of an alcoholic beverage of a given alcohol (C₂H₅OH) concentration so that it does not cause intoxication (hangovers occur only when intoxication sets in; otherwise the alcohol is easily metabolized by the body)?”
- “What should the relationship be between the rate of alcohol intake, the time period of drinking, the strength of the liquor, and the time taken by the body to revive?”

To achieve the above aims, Gaurav represented the stomach, small intestine, and blood as control volumes, made suitable assumptions, consulted several books (including encyclopedias), performed material balances on ethanol, water, and total mass, and concluded

- “To avoid intoxication, a normal person should drink beer at the rate of less than 790 ml h⁻¹.”
- “To be in a position to drive home safely after a party, a normal person should drink less than 90 ml of whiskey over a two-hour period.”

While the actual numbers above may be subject to debate, the beauty in application of the material balance principles and the social relevance is clear.

**Methyl Isocyanate Poisoning from Union Carbide Factory at Bhopal**
_(Sagnik Basuray)_ (Material and Energy Balances)

The motivation for this student was to see whether or not the biggest chemical factory disaster in India could have been avoided, using concepts that he had learned in his first chemical engineering course. It is well known that there were at least five levels of safety measures at the factory, including a flame tower to burn vented gases, all of which either failed or were not operational when the gas leak occurred. Sagnik performed material balance calculations on the relevant sections of the plant, which included tank No. 610 that leaked, and calculated the composition of the various streams for different inputs. Different inputs were considered to determine which inputs would have still averted the disaster. He also carried out energy balance calculations to conclude that even if the flame tower had been operational for burning away the released gas, it would have collapsed because it was structurally incapable of handling such a high rate of energy inflow as 1.05 MJ min⁻¹; therefore it was designed badly. Sagnik used the known civil engineering data on the tower to draw this conclusion.
From an instructor’s viewpoint, a more refined analysis is needed before drawing such a strong conclusion, but the rudiments of good application are evident.

**Thermodynamics of Breathing**  
(Narendra Dixit) (Engineering Thermodynamics)

Narendra Dixit wrote, “the process of breathing has always been a marvel to human intellect. It is something that goes on and on, sustaining life under the most critical of circumstances, stopping only when there is no more life.... It is an enlightening exercise to identify how much energy one spends (or consumes) to sustain one’s own life.”

His well-identified objectives were

- To formulate a thermodynamic model of the respiratory apparatus
- To analyze the thermodynamics involved in the mechanism of breathing

After referring to several medical and other books, he divided the process of breathing into two segments: a nasal process involving processes at the nose, and a post-nasal process involving processes in the lungs. He modeled the post-nasal breathing process as a cylinder with a frictionless piston with three openings for air, CO\textsubscript{2}, and O\textsubscript{2}. With suitable other assumptions, he determined that the total work done during each breathing cycle is a low 0.03 J, the entropy change is only $3.42 \times 10^{-4}$ J K\textsuperscript{-1} per cycle, and the irreversibility is 0.1026 J per cycle. He concluded by marvelling at the superiority of natural mechanisms from a thermodynamic viewpoint.

**Analysis of a Spirit Lamp Using Material Balances**  
(Gaurav Misra) (Material and Energy Balances)

The motivation for Gaurav Misra was his fascination with the simple spirit lamp. Based on material balance principles and certain assumptions (the limitations of which he was acutely aware of), he not only derived expressions to achieve the following objectives, but also suggested simple experiments to obtain numerical values of the relevant quantities. His objectives included

- Obtaining an expression for the rate of flow of atmospheric air to the lamp
- Obtaining an expression for the rate of rise of fuel in the wick
- Obtaining an expression for the fuel efficiency of the lamp
- Relating the parameters of the wick with the efficiency of the lamp

It is worthwhile to point out that the student had no exposure to fluid mechanics at the time and had to acquire some fluid mechanics principles from senior students and books to be able to attempt analysis of the relevant parts of his project.

**Thermodynamic Analysis of Glass-Fiber Production**  
(Manoj Kumar Pandey) (Engineering Thermodynamics)

Manoj decided to apply thermodynamic principles to the glass-fiber production process. He focused on

- Estimation of the power input required
- The effect of varying power input on viscosity (a narrow range in viscosities is required for good-quality fiber)
- Analysis of the cooling system and estimation of temperatures of the fiber exiting the nozzle

He chose suitable control volumes for his analysis and estimated a power of 15 KW to produce about 10 Kg h\textsuperscript{-1} of fiber. He also found that the power input should be controlled to within less than 1% variation for good quality fiber and that the temperature of the fiber exiting the nozzle is 175°C.

**Generation of Electrical Power Using Automobile Exhaust**  
(Prateek Jain) (Material and Energy Balances)

Prateek Jain considered a small dynamo at the end of a tailpipe to find out whether automobile exhaust can be used to generate electricity. He gathered background information on engines that use compressed natural gas as fuel, exhaust compositions, temperatures at exhaust, and other relevant information. Then he performed material and energy balances on the engine and tailpipe and found that the velocity of exhaust gases from the tailpipe could be used to drive a dynamo that could light a small bulb.

There have been many exercises that this instructor found interesting, although only a few are described above. The more common exercises included industrial data consistency checks using real data obtained from industry, material and energy balances, and exergy/irreversibility analysis in engineering thermodynamics.

**STUDENT FEEDBACK**

The above examples are good exercises, and it is obvious that the students thoroughly enjoyed the work. Over the past four years, an estimated 65% of the students expressed appreciation to the instructor for assigning this exercise because they felt they learned something useful. Two especially perceptive students thanked the instructor for not helping them at all, realizing that no help was the best path to learning. A few students who are currently graduate students pursuing their doctoral degrees in the U.S. have said that the CFA exercise is the only thing they still remember from the course after four years.

Except for five students (over the past four years), the rest of the students had no comments. Two of the five respond-
ing students said that the exercise was not useful to them, and the remaining three wanted the instructor to assign project titles. Among these five responses, three were received the first time the exercise was assigned and the other two were received the second time it was assigned. No adverse comments have been received since then. This indicates that the instructor perhaps became better at making the students appreciate the purpose of the exercise through mentioning it more often at appropriate junctures during the semester.

The class average in this exercise is usually around 65%, save for the first time it was given when it was 54.1%. This is probably because in subsequent years, copies of good reports from the previous years were made available as reference material.

VARIATION FOR COURSES WITH LIMITED DEPTH

The CFA exercise, in the form mentioned above, may not be suitable for courses with limited depth since they cover so many different principles in just a superficial manner. For such courses, the following exercise was assigned:

This exercise expects students to “adopt” a chemical (biochemical) industry by the third week of classes. Then, students should relate the principles taught in class to the actual processes taking place in the “adopted” industry and analyze, preferably, one aspect in detail. A concise report submitted a week before the last day of classes will be evaluated strictly on the following aspects:

- Link between fundamentals and actual processes: 40%
- Analysis of the actual process(es): 30%
- “Reality” factor: 20%
- Presentation (mainly communication): 10%

If students visited the industry, they received the 20% “reality” factor. If they decided to perform a library exercise, then the closeness of their report to actuality formed the basis for marks on that aspect.

APPARENT CHALLENGES WITH THE EVALUATION ASPECTS

Although the instructor did not face any real difficulty with the evaluation except for the time needed to grade reports for large classes (five to six full days), some colleagues raised questions about certain evaluation aspects. It is worthwhile mentioning some of those apprehensions:

How can undergraduate students do independent work?

The student exercises show that even first-year undergraduate students are capable of visiting an industry, independently, and choosing novel aspects for analysis when encouraged to do so.

How can you find out if a problem was taken from some unseen source? How do you judge originality?

It is known that as long as grades are important, some students will cheat to get the highest possible grade. However, the instructor usually knows the level of students’ knowledge (at least on the imparted subject) in a class taught by him, and therefore he has a notional expectation. On that basis, if a report is suspicious, the instructor can have a one-on-one interview with the student. On the average, this instructor needed to interview approximately 20 students out of a 80-student class. By asking the correct questions, most of which are technical, it was easy to determine if the student had cheated. If just the problem was picked from some source and the analysis was done by the student, zeroes were given for the relevant aspects in the evaluation (such as originality in approach, focus level, and original contribution) so out of a possible 100 points, the student received marks in the thirties. This prevents cheating to a large extent in subsequent years because of the way the word spreads among the students.

The fact that no complaint/comments that someone got away with submitting “lifted material” have been received from an acutely grade-conscious set of undergraduates over the past four years, coupled with verbal comments that the instructor has been very fair, shows that it is possible to effectively weed out the cheaters.

ASPECTS OF THE LEARNING PROCESS

- Course Fundamentals It is the instructor’s opinion that the students who scored above 50% (recall that the class average is usually around 65%) had picked up the course fundamentals to a desirable degree because they were able to view an aspect of their choice from, say, a material-and-energy-balances point of view.

- Self-Reliance Since the instructor denied any help at any stage of the project, students were forced to become self-reliant. It was initially difficult not to be nice to the students when they asked for help, but in the greater interest of the students, this instructor became accustomed to it.

- Rational Choice The students were asked to make a rational choice among the innumerable ways they could have approached the project and to be responsible for it. For example, if they did not obtain proper data from an industry and therefore had to change their project midway through it, they realized that they were completely responsible for choosing that particular industry in the first place.

- Creativity/Lateral Thinking A wide scope exists for exhibiting one’s creativity in such an exercise because it invites the student to see all aspects from the point of view of the fundamental principles. Even when the student is not inherently creative, but desires to be creative, a significant amount of time (about half the semester) is provided to the student to apply himself toward that goal. In the instructor’s judgment, about 20% of the students were creative through effort. Also,
creativity could be manifest in many aspects of the exercise, such as creative choosing, creative focusing, creative analysis, and creative presentation. Students who were creative were richly rewarded in the “originality in approach” and/or the “original contribution” categories of the evaluation. The exercise also provided good scope to exhibit lateral thinking, as demonstrated in some of the samples discussed in the earlier section. Some students also showed their “synthesis” abilities in their choice of the problem for analysis.

**Focus**  The focus level in almost 90% of the reports was acceptable, and in an estimated 60% of the reports it was good.

**Communication and Professional Appearance of Reports**  This exercise (deliberately) did not have a pre-determined format for reports in order to help the students think about how to present their work in an effective fashion. When a certain format is provided, it tends to curtail the freedom of organization, and in many cases, organization different from the traditional one is more effective in communication. The instructor estimates that about 80% of the class communicated their work reasonably well, and 50% of the class did it well (one reading was sufficient for understanding) — a fact that was surprising to the instructor in the first two years. Also, an estimated 60% of the reports had a very professional appearance. This indicates that when something is assigned as their responsibility, the students do a good job in ways not expected of them.

**Helping Others**  The students at I.I.T. Bombay are so highly competitive that on many occasions their “cutthroat” competition has saddened this instructor. In this particular exercise, however, it was a pleasant surprise to find classmates helping each other—be it in discussing possible ideas, sharing instructive web-site addresses, or teaching word-processing skills—while at the same time protecting their novel ideas. In their reports, many students acknowledged the help they received from their friends.

**Teamwork**  It is true that the CFA exercise does not promote teamwork, but the importance and value of teamwork is emphasized in tutorial sessions throughout the course. During the sessions (on the average, one hour per week, per course), the students are expected to work out problems given in the problem sets. Normally, teaching assistants grade the performance in the problem sets, which carries a 5% to 10% weightage toward the final grade. In the courses taught by this instructor, the class is divided into 10 to 15 groups of 5 to 6 students each. The problem sets are distributed about a week prior to the tutorial session, and the students are given complete freedom to discuss the problems with anyone. The only requirement is that they learn how to solve the problem. During the tutorial session, one student from a group, chosen by drawing lots, works out the problem on the board and is graded by the instructor for correctness in approach and answers to questions by the class/instructor (90%), and communication to the class (10%). Whatever marks the student earns are given to the entire group, thereby making the student responsible for the groups marks— or, in other words, the group is made responsible for each member knowing the solution. Ten percent weightage toward the final grade, coupled with the ignominy before their classmates if they do not prepare, are significant motivating factors for the majority of students to take the tutorials seriously. Thus, the importance of teamwork is emphasized.

From a broader perspective, Prausnitz\(^{5}\) opined that chemical engineering is one of the humanities that has a deep human intent and that the role of context should be integrated into the chemical engineering curriculum rather than being delegated to a course in humanities. Felder\(^2\) has said that if we are to produce engineers who can solve society’s most pressing problems, we must somehow convey that problems in life are open-ended and convergent production (generation of the right answer to a well-defined problem), which is synonymous with academic excellence in engineering, is only one of the skills required. This instructor believes that the CFA exercise takes us a step closer toward realizing their suggestions.

**ACKNOWLEDGMENTS**

I thank the students of Material and Energy Balances (Introduction to Chemical Engineering), Thermodynamics, Elements of Chemical Engineering, and Bioprocess Principles classes that I have taught over the past four years for their enthusiastic participation in the CFA exercise. I also thank my colleague, Professor Raghunathan Rengasamy, for his suggestion to communicate this exercise as a paper to Chemical Engineering Education. In addition, I thank my colleagues, Professors Kartic Khilar and Hemant Nanavati for their input.

**REFERENCES**

AUTHOR GUIDELINES

This guide is offered to aid authors in preparing manuscripts for Chemical Engineering Education (CEE), a quarterly journal published by the Chemical Engineering Division of the American Society for Engineering Education (ASEE).

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Phone and Fax: 352-392-0861
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