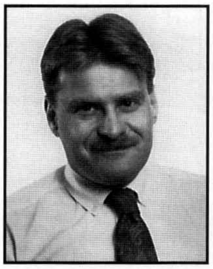
CHEMICAL PRODUCT DESIGN

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

The capstone senior-design experience has traditionally involved design of a new process to make a familiar product. With the exception of the introduction of process simulators, changes over the past 50 years have been subtle. For example, the focus on environmental issues such as pollution prevention using alternative solvents or alternative reaction paths, waste stream treatment, and recycling has become popular. Similarly, projects in the "emerging" technologies such as materials and biochemical engineering are more common today. In a recent article, Cussler made a strong case for including product design as part of the capstone, chemical engineering design experience.[1] He argues that the future of the chemical engineering profession is more consistent with the design of new chemical products and less with the design of chemical processes to make existing chemicals. His statistics show that over the past 20 years, there has been a shift in corporate and hiring practices so that more graduates go to work for companies that develop new chemical products than companies that use traditional, continuous chemical processes.

In this paper, a senior design assignment specifically involving product design is described. Three product designs completed by students are described, two in detail. The implications of this type of assignment and its potential as a framework for interdisciplinary team projects are also discussed.

Joseph A. Shaeiwitz *received his BS from the University of Delaware and MS and PhD from Carnegie Mellon University. His professional interests are in design, design education, and outcomes assessment. He is coauthor of the text* Analysis, Synthesis, and Design of Chemical Processes, *published by Prentice Hall in 1998.*



Richard Turton *received his BSc from the University of Nottingham and his MS and PhD from Oregon State University. His current research interests are focused in the area of fluidization and its application to the coating of pharmaceutical products. He is coauthor of the text* Analysis, Synthesis, and Design of Chemical Processes, *published by Prentice Hall in 1998.*

BACKGROUND

Cussler and Moggridge[2] define four types of chemical products. They are:

- *New specialty chemicals*
- *Products whose microstructure rather than molecular structure creates value (e.g. paint)*
- *Devices causing chemical change (e.g. a blood oxygenator or the electrolytic device described later in this paper)*
- *Virtual chemical products (e.g. software to simulate chemical processes or estimate physical properties)*

In this paper, a fifth category of chemical products is included: technology that uses chemical engineering principles. Cussler and Moggridge also define one possible framework for the product design process.[2] It contains four steps: identify customer need, generate ideas to meet that need, select from among the ideas generated, and manufacture the product. They also suggest that one key difference between process design and product design is the entrepreneurial skills required of the engineer in product design.

In process design, the decision on what to manufacture does not usually involve the process engineer. He or she usually focuses on the calculations and engineering judgment necessary to design and to optimize the process and/or keep it running smoothly and efficiently. In product design, a combination of business and technology skills is required.

The engineer shares responsibility for identifying the product and for its design and manufacture. The responsibility for identifying the product may be shared with those who have business backgrounds, and the responsibility for its design and manufacture may be shared with other types of engineers. This is the type of interdisciplinary effort that companies now favor.

STUDENT ASSIGNMENT

One goal of this assignment was to give students an experience in chemical product design. A second goal was to determine whether chemical product designs could be used successfully as capstone projects. The framework for the student assignment was our unique, year-long design experience led by a student chief engineer.[3] In this case, a group of fourteen students under the direction of one student, who was selected as chief engineer, was given the during the second semester. Faculty played roles in this assignment—one was

TABLE 1
Product Designs Recommended by Students

Product	Notes
❑ ***Products designed***	
Chlorine alternatives in pools	Device to convert salt to chlorinated disinfectant
Magnetic refrigerator	Based on magnetocaloric effect—no compressor
Zebra mussel control	Removal and control of mollusks that foul water intake pipes in water treatment plants and power plants
❑ ***Chosen by client for further evaluation and recommended by students for complete design (but not actually designed)***	
Removal of silver by chitosan	Using crustacean shells as adsorbent
Peptide production	Production of kilogram quantities of peptides from amino acids
Starch-based polymers (polylactic acid)	Novel product—biodegradable polymer
Ethanol-water separation using molecular sieves	Method to purify past azeotrope
❑ ***Also chosen by client as being worthy of further evaluation***	
Asbestos removal system	Air filtration system to remove asbestos continuously
E. coli detector	On meat packaging to determine freshness
Additives to assist in garbage decomposition	Enzymes, proteins, etc.
Medical disposal service	Furnace to convert stainless steel needles to recyclable metal
Geothermal heat pump	Home heat pump using geothermal temperature difference
Anti-nerve gas injection system	Automatic sensor that commences injection when nerve gas is detected
Natural pesticides	Naturally produced chemicals derived from plants like tobacco
Fuel cells	For cars, etc.

... a group of fourteen students under the direction of one student, who was selected as chief engineer, was given the open-ended assignment of identifying product design opportunities. The goal for the first semester was to identify as many opportunities as possible and then progressively narrow the field until one or more would be selected for design during the second semester.

the "client" and the other was the "vice-president of the students' company."

With reference to the product design framework discussed earlier, the students were required to complete the first three steps during the first semester and the fourth step during the second semester. Because the students were not working for an actual company, some liberties were taken with the definition of the customer. The client was the customer, but the client's company had no specific business. Instead, the client was a venture capitalist looking for opportunities for investment. Therefore, it was incumbent on the students to determine the potential need (customer base) for their ideas and to sell these ideas to the client.

Students were given a limited background on product design. The basics were introduced at a level of detail roughly equivalent to that described in the "background" section above. They were also given the printed materials listed in references one and two. There were weekly client meetings, which are a standard feature of this capstone experience.[3] For the first few weeks, these meetings were used to clarify, or at least narrow, the definition of product design, to determine which of their ideas qualified as product design, and to suggest product design ideas for their consideration.

RESULTS

The student group generated more than 100 ideas within the first month or so of the first semester. Many of these ideas were the result of brainstorming activities and were rejected rather quickly. By the midpoint of the first semester, 17 ideas were recommended by the students for further study, and 15 of them were chosen by the client for further evaluation. These are listed in Table 1, which includes a brief description of each. After further evaluation, the students recommended seven ideas for design. Three were chosen for complete design. The group of 14 students was subsequently subdivided into three smaller groups for the product designs, which were completed during the second semester. Each group had a group leader, and the chief engineer was responsible for coordinating all three designs and representing the group to the client.

The eight ideas that were not recommended for complete designs were in that category because students determined that either these products already existed and current markets were saturated, or sufficient information did not exist in the open literature for a com-

TABLE 2
Investment/Equipment Summary for Salt Chlorination System

	Commercial	Residential
Number of plates in cell	21	11
Plate spacing	0.5 cm	0.5 cm
Area of one plate	68 cm^2	17 cm^2
Length of piping	50 ft.	50 ft.
Number of elbows	10	10
Number of Ts	2	2
Pipe diameter	4" (10.2 cm)	2" (5.1 cm)
Cell cost	$177	$23
Total cost of piping	$98	$42
Hopper	$80	$80
Salt sensor cleaner	$20	$20
Sensor and controller	$1,500	$1,500
Initial start-up salt	$500	$125
Sand filter	$300	$160
Pump	$760	$190
AC/DC converter	$300	$250
Total cost	***$3,735***	***$2,390***

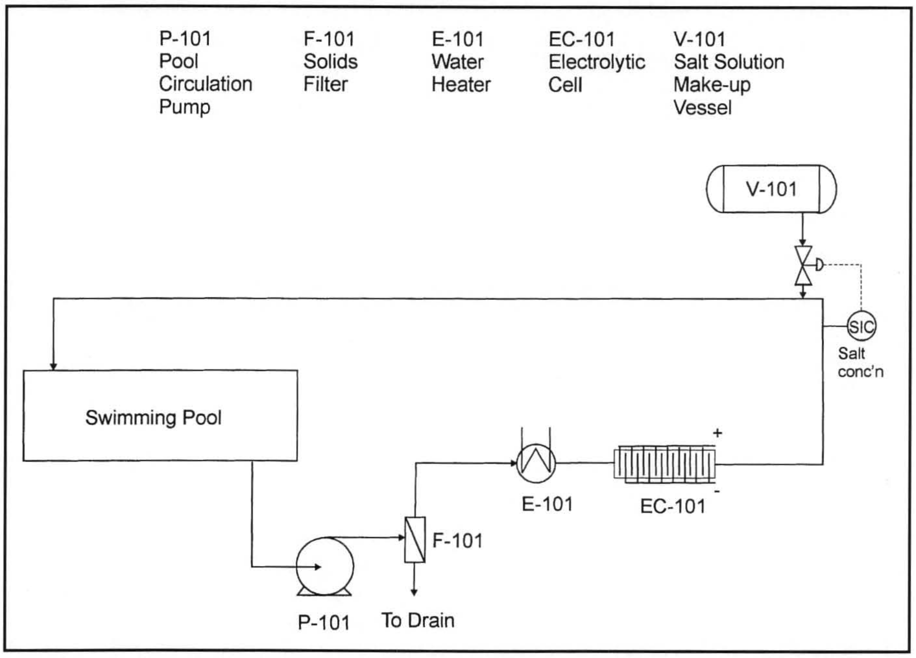


Figure 1. *Process flow diagram for salt chlorination cell and pool pumping system.*

plete product design. This latter reason was the primary consideration for selection of the three products for final design. We determined that sufficient information was available for a design, and that experiments would not be needed to determine key parameters.

A short description of the zebra mussel control technology product is presented below. Then descriptions of the salt chlorination device and the magnetic refrigerator are presented in greater detail. Additional descriptions of all of these products can be found on our web site.[4]

ZEBRA MUSSEL CONTROL

In 1986, zebra mussels were first introduced in the United States. They were discovered in the Great Lakes, and their most likely source was the ballast water of ships coming from Europe. Their arrival became notorious when water-intake pipes all over the Great Lakes region started to become clogged with their masses. It has been determined that a 4.5-ppm aqeous alkylbenzyldimethylammonium chloride solution can be used for a one-time kill of zebra mussels and that continuous addition of 3-ppm hydrogen peroxide inhibits further infestation.

The deliverables for this design included a process flow diagram (PFD) for the pumping/delivery system and an economic analysis of the annualized cost of installing and operating the delivery system. A grating was designed for the water-intake pipes to deliver these chemicals. The project also included design of the pumping system and an analysis of the turbulent fluid mechanics at the injection point to ensure complete coverage and adequate dispersion/mixing of the injected chemicals. More details of this design are available elsewhere.[5]

> ***. . . one goal was to give students a unique experience in chemical product design. A second goal was to determine whether chemical product designs could be used successfully as capstone projects. We believe that the completed designs suggest that both goals were achieved.***

CHLORINE ALTERNATIVES IN POOLS

The salt chlorination device uses an electrolytic cell to electrolyze salt into hypochlorous acid, the active pool disinfectant. This device eliminates the almost-daily requirement to add chlorinated chemicals to a pool. It also reduces the chlorine smell because the device is in the "pump room." Additionally, the bleaching and irritating effects of chlorine in the pool are diminished because the hypochlorite is concentrated only near the electrolytic cell. It either does not exist within the pool or its concentration is much lower in the pool.

The deliverables for this part of the project included a PFD for the pool pumping system, a design of the electrolytic cell, a cost analysis of the components of the system, and an analysis of the incremental cost of such a device versus the time saved by the pool owner. Decision variables for the optimizations included the pool operating temperature, number of electrode plates in the cell, and their spacing.

The electrolytic cell and the pumping system were designed as shown in Figure 1. Specifications and a list of component parts are listed in Table 2 for both a commercial and residential pool. An interesting feature of this design is the need to quantify the cost of convenience of such a device. The question is how much a home or commercial pool owner would be willing to pay for the convenience of not having to deal with adding chemicals on a daily basis. It was estimated that the residential pool owner would actually save several thousand dollars per year (based on seasonal operation, more for annual operation) by using this device. The additional cost of this device, however, adds $2,000 to $3,000 to the initial cost of the pool. With a payback period of approximately one year, the economics are clear. This does not mean, however, that electrolytic salt chlorination devices will be easy to sell as add-ons. Clearly, this is a marketing issue that cannot be answered without customer surveys.

MAGNETIC REFRIGERATOR

Magnetic refrigeration is based on the magnetocaloric effect. This effect, discovered in 1881, is defined as the response of a solid to an applied magnetic field, which is manifested as a change in its temperature.[6] This effect is obeyed by all transition metals and lanthanide-series elements. When a magnetic field is applied, these metals tend to heat up. As the field is applied, the magnetic moments align. When the field is removed, the ferromagnet cools down as the magnetic moments become randomly oriented. Gadolinium, a rare-earth metal, exhibits one of the largest known magnetocaloric effects. It was used as the refrigerant for many of the early magnetic refrigeration designs. The problem with using pure gadolinium as the refrigerant material is that it does not exhibit a strong magnetocaloric effect at room temperature. More recently, however, it has been discovered that arc-melted alloys of gadolinium, silicon, and germanium are more efficient at room temperature and that alloys with the appropriate temperature properties for a home refrigerator exist. [7]

The main difference between the magnetic refrigerator and a conventional refrigerator is that the magnetic refrigerator needs no compressor, the most inefficient and expensive part of the conventional gas-compression system. In place of the compressor there are small beds containing the open-ended assignment of identifying product design opportunities. The goal for the first semester was to identify as many opportunities as possible and then progressively narrow the field until one or more would be selected for design magnetocaloric material, a small pump to circulate the heat transfer fluid, and a drive shaft to move the beds in and out of the magnetic field. The heat transfer fluid used in this process is water mixed with ethanol. This mixture is used instead of traditional refrigerants that pose a threat to the environment.

The ultimate goal of this technology is to develop a standard refrigerator for home use. The use of magnetic refrigeration has the potential to reduce both operating and maintenance costs when compared to the conventional compressor-based refrigeration. The major advantages to the magnetic refrigeration technology over compressor-based refrigeration are potentially simpler design technology, a less serious environmental impact, and lower operating costs.

The deliverables for this design included a device design, the choice of working fluid, a cost analysis of the component parts for a prototype, and an analysis of the cost reduction per unit realized during mass production. The process flow diagram for the magnetic refrigeration system is shown in Figure 2. The component parts list for a prototype and operating costs are shown in Table 3. An ethanol/water mixture serves as the heat transfer fluid for the system. The magnetocaloric beds simultaneously move up and down, into and out of the magnetic field. When the beds are in the magnetic field, they heat up, and when they leave the magnetic field, they cool down. The ethanol/water mixture passes through the hot heat exchanger (E-101 in Figure 2), which uses ambient air to transfer heat to the atmosphere and cool the mixture. The mixture then passes over the copper plates attached to the nonmagnetized cooler magnetocaloric beds and is cooled. The cooled ethanol/water mixture then passes through a heat exchanger (E-102), where it exchanges heat with ambient air sucked through a fan (F-101). This cooled air passes into the freezer to keep the freezer temperature at approximately 0°F. The cold air from the freezer is blown into the refrigerator by the freezer fan (F-102). The temperature of the refrigerator section is kept at approximately 39°F. The ethanol/water mixture then gets heated as it passes through the copper plates attached to the magnetized warmer magnetocaloric beds.

TABLE 3

Capital and Operating Costs for Magnetic Refrigeration

Capital Costs	*$*
Hot Heat Exchanger	$ 175
Cold Heat Exchanger	175
Magnetocaloric Material	80
Drive Shaft	50
Magnet	40
Tubing	35
Pump	20
Defrost Equipment	90
Fan Motors	80
Capillary Tube Dryer	35
Total Start-Up	$780
Operating Costs	*$/Year*
Drive Shaft Electricity	$40.00
Pump Electricity	2.50
Total Operating	$42.50

In the design of the magnetic refrigerator, students had to use their knowledge of fluid mechanics, heat transfer, and thermodynamics. They chose the ethanol/water solution by investigating the thermodynamics of several different mixtures. The pump and tubing system for circulating the ethanol/water mixture was designed and optimized. The heat exchangers were also designed. These are typical chemical engineering calculations.

Some nonchemical engineering considerations were also necessary, however. A system had to be designed to move the two sets of beds of magnetocaloric material in and out of the magnetic field. After consultation with mechanical engineers, a chain-and-sprocket system was chosen. A more complete design would require a control system. This was not included in this project, however. Another consideration

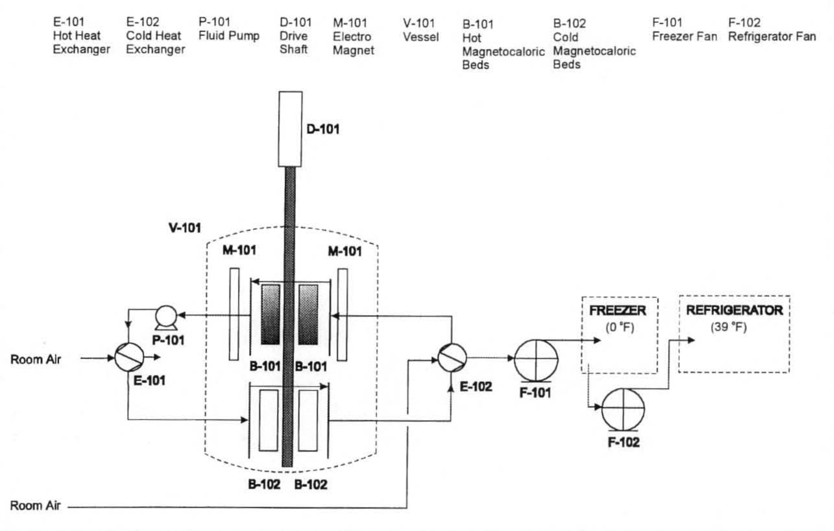


Figure 2. *Process flow diagram for magnetic refrigeration.*

was the cost to mass produce refrigerators based on the estimated cost of the prototype. After consulting with industrial engineers, students discovered there is a learning curve that can be used to estimate the cost to mass produce an item, based on the number of units manufactured. The cost per unit to produce millions of units approaches one-half the cost of the prototype. Only after analysis was completed, was the cost of the magnetic refrigerator found to be competitive with existing refrigerators.

DISCUSSION

We believe this project was a success. We were unsure, however, of the outcome until late in the second semester. As stated earlier, one goal was to give students a unique experience in chemical product design. A second goal was to determine whether chemical product designs could be used successfully as capstone projects. We believe that the completed designs suggest that both goals were achieved.

The assignment on the year-long project is always open-ended, but this assignment was more open-ended than usual. Given the novelty of this assignment, our level of discomfort was equivalent to that of the students early in the project. Normally, we go into one of these open-ended assignments with at least one idea for a project direction, though we expect that students will identify many feasible alternatives. In the worst-case scenario, the client can drive the project toward that default option. In this case, the students deserve credit for pulling these projects together. It was particularly satisfying that, for all three projects, they identified an objective function and decision variables to do optimization, even though these functions and variables were different from those normally used in traditional process designs.

After the final presentation, the group was interviewed and asked how they felt about having done this project instead of a more traditional chemical process design (as was done by their peers in the other half of the class). All the group members said they felt it was a positive experience. Their opinion is best summarized by one response: "It was certainly more interesting than doing another process design." This is a reflection of the design orientation in our curriculum, in which students had already completed a traditional process design in the sophomore and junior years and had worked on different aspects of a traditional chemical process in another portion of the senior design class. On the semester course evaluations, there were no anomalies, one way or the other. The instructor evaluations were similar to previous years, there were no negative comments about the product designs, and there were a few positive comments.

In retrospect, all three of these projects would be excellent opportunities for multidisciplinary team experiences. As was described for the magnetic refrigerator, there were aspects appropriate for mechanical and industrial engineers. The salt chlorination device would have benefited from the involvement of someone with a business background who could help students understand potential issues such as consumer acceptance of these devices, determining target prices, number of units to be manufactured, and development of a business plan for the new product. The zebra mussel project would normally have benefited from the contributions of a biologist, but it turned out that one of the students (who was the source of the idea) was already an expert on zebra mussel biology from a high school science project. Chemical engineering departments or engineering colleges wishing to implement a multidisciplinary design experience may wish to consider a product design project for this purpose.

CONCLUSION

A unique capstone design experience involving product design was quite successful. Students in groups of four or five, led by a chief engineer, completed three such designs. One product was chemical process technology and two were devices. Students did an excellent job in applying chemical engineering principles to these designs and said they felt very positive about the experience. Product designs such as these offer the possibility for multidisciplinary design projects, potentially involving engineering, science, and business disciplines.

ACKNOWLEDGMENTS

The following students from the WVU class of 2000 participated in this project: Brian J. Anderson as chief engineer; Matthew Billiter as group leader for the magnetic refrigerator project; Jason Tennant as group leader for the salt chlorination device project; Christopher Yurchick as group leader for the zebra mussel control project; Kelli Adams, Nicolas Martino, Matthew Miller, Matthew Plants, Lia Porco, Robert Rappold, Diana Roseborough, Lynn Roseborough, Byron Walker, and Bonnie Welcker as group members.

REFERENCES

1. Cussler, E.L., "Do Changes in the Chemical Industry Imply Changes in Curriculum?" *Chem. Eng. Ed.*, **33**(1), 12 (1999)
2. Cussler, E.L., and G. Moggridge, *Chemical Product Design*, Cambridge Press, New York (2001)
3. Shaeiwitz, J.A., W.B. Whiting, and D. Velegol, "A Large-Group Senior Design Experience: Teaching Responsibility and Life-Long Learning," *Chem. Eng. Ed.*, **30**(1), 70 (1996)
4. Web site located at: <http://www.cemr.wvu.edu/~wwwche /publications/projects/index.html>
5. Shaeiwitz, J.A., and R. Turton, "Chemical Product Design," *Chemical Engineering Education in the New Millennium, Topical Conference Proceedings*, AIChE Annual Meeting, Los Angeles, CA, 461, November (2000)
6. Gschneidner, K., V. Pecharsky, and C. Zimm, "Magnetic Cooling for Appliances," *International Appliance Technical Conference Proceedings*, 144, May (1999)
7. Gschneidner, K., and V. Pecharsky, "The Giant Magnetocaloric Effect in $Gd_5(Si_xGe_{1-x})_4$ Materials for Magnetic Refrigeration," *Advances in Cryogenic Engineering,* Plenum Press, New York, 1729 (1998) ❑