DESIGN PROJECTS OF THE FUTURE

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It is generally accepted that the chemical engineering profession is in a state of change. Fewer graduates from U.S. chemical engineering departments are entering the petroleum, petrochemical, and chemical industries, since most expansion in these industries is not in the United States. More graduates from U.S. chemical engineering departments are entering product-based industries (*e.g.*, pharmaceutical, food, new materials) rather than the traditional commodity-chemical-based industries (ethylene oxide, benzene, sulfuric acid).[1, 2] Therefore, changes in the undergraduate chemical engineering curriculum—which has been static for about 40 years (not counting advances in computing)—are imminent, if not already in progress.

Three significant changes in the chemical engineering curriculum are under way.[3] First of all, biology is now considered to be an "enabling" science, along with chemistry and physics. Some education in the life sciences will soon be required for accreditation.[4] Secondly, chemical engineers need to be taught about product design, either instead of or in addition to process design. It will become more important to teach batch operations, since the manufacture of new chemical products will certainly involve batch rather than continuous operations. Finally, over the past generation, advances in chemical engineering research have involved the ability to understand and to manipulate phenomena at the colloidal, nano, molecular, and atomic scales. A key issue is the effect on macroscopic properties of colloidal-, nano-, molecular-, and atomic-scale phenomena, *i.e.*, structure-property relations. It is time these advances became part of the undergraduate curriculum.

Radical changes to the traditional chemical engineering curriculum have been proposed.[3] Changes are on the horizon, although the speed and degree of implementation of these changes is not yet obvious. It could also be argued, however, that traditional chemical process engineering must still be taught, because the soon-to-retire baby boom generation must be replaced by newcomers equally capable of operating, maintaining, and updating existing chemical plants.

Given the importance of the capstone experience in the undergraduate education process, a question that arises when considering curriculum changes is: *What will the capstone chemical engineering design project of the future look like?* It is virtually certain that the capstone chemical engineering project of the future will not involve sulfuric acid or ethylene oxide production. Instead, it may have a life science basis. It may involve design of a product. It may involve multiscale phenomena, *i.e.*, the effect of nano- or molecular-scale interactions on the performance of the product. It is more likely to involve batch processing than continuous processing. And, it is also possible that manufacture of items and unit packaging—two concepts far removed from traditional chemical engineering—will be included.

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In an effort to initiate a new capstone-design paradigm, the yearlong capstone design project at West Virginia University for 2003-04 and 2004-05 involved biologically oriented, multiscale product designs. These two projects are described in this paper. More details are available elsewhere[5] and from the authors.

CLASS ORGANIZATION

In the senior year of chemical engineering at West Virginia University, the entire class works on a large project for two semesters under the direction of a student chief engineer. More details are presented elsewhere.[6] Briefly, faculty members play roles: one is the client, for whom the students are "hired" to complete a design project; another is the "vice president" of the students' company, who helps the students with technical matters. The student chief engineer divides the class into groups, each headed by a group leader. The role of the chief engineer is to represent the entire team to the client and to provide leadership from the "big picture" perspective. The group leaders receive assignments from the chief engineer and are responsible for completing the work within their groups. Assignments are deliberately vague and open ended. One goal is to force students to define their own work statement, with input from faculty members. Another is to learn material not normally taught in class. The exact topics students must learn are a function of the project. A further goal is to make students realize that they will have to continue learning new material throughout their careers, and that they have the ability to do so.

In the fall semester, the project involves researching alternatives and a feasibility study. For example, in ice cream production, the assignment was to identify, screen, and recommend food products for production, with attention focused on products that have low-fat and/or low-carbohydrate alternatives. Students set their own direction with a minimum of input from the instructors. The client chooses one alternative for design in the spring semester. This is really the only opportunity for the instructors to influence the direction of the project; however, the client's choice is always one of the top two student recommendations.

ICE CREAM PRODUCTION

This project was completed by 26 students over the course of the entire 2004-05 academic year. It started with a very open-ended assignment: to investigate opportunities in food processing, particularly those involving low-fat and low-carbohydrate alternatives. The market for these foods was to be analyzed, and the issues associated with producing the low-fat and low-carbohydrate alternatives were to be identified. A summary of the colloidal- and molecular-scale issues identified by students is shown Table 1. Production of any of these

TABLE 1
Examples of Colloidal- and Molecular-Scale Processing Challenges in Food Manufacturing

Product	Processing Challenge
Ice Cream	Ice crystal formation must be kept to a minimum. Otherwise, the ice cream has a grainy texture. Nut and fruit size must be controlled to control the rheology. Processing conditions must be controlled to prevent nuts and fruit additives from becoming soggy. One method for making low-fat ice cream have the same mouth feel as regular ice cream is slow churning, a proprietary process of Edy/Dreyers.[5] By churning the ice cream at higher pressures and lower temperatures, smaller, more dispersed fat globules are formed that have similar mouth feel to regular ice cream.
Cookies	Almond flour is often substituted for wheat flour in low-carbohydrate cookies. Since almond flour contains more fat, the result is a chewier cookie. Granulated sugar is required in cookie manufacture so that the sugar will spread throughout the cookie during baking. Coarse sugar results in cracking. This has implications as to which sugar substitute can be used in low-carbohydrate cookies. Reduced-fat cookies require longer baking times to allow the existing fat to coat the flour and sugar particles. For sandwich cookies to stick together, the surface energy of the solid must be higher than that of the filling. One way to accomplish this is to raise the temperature of the filling and add more fat to the filling, both of which reduce its surface energy. (This is also true for ice cream sandwiches.)
Bread	Protein and fiber are often substituted for wheat flour in low-carbohydrate bread. Binding agents are required to hold these ingredients together. Dough conditioners are added for strength.
Cereal Bars	Binders are added to hold the cereal pieces together. They crosslink to form a flow-resistant structure. There are two common binders. One involves dipolar interactions between OH groups on glucose molecules in the binder and the cereal pieces. The other involves COO^- groups bonding covalently with the cereal pieces.

products would make a good design project. Each involves batch processing of a product as well as manipulation at the molecular or colloidal levels to obtain desired macroscopic properties. Another feature involved, but traditionally unfamiliar to chemical engineers, is packaging.

Students used product screening methods to rank the alternatives.[7] Ultimately, ice cream production to capture 1% of the domestic market was chosen for a complete design. Production of 1.75-quart containers plus some novelties (pops and bars, in this case) were included in the design. Ice cream production involves traditional chemical engineering, product design, and multiscale analysis. It involves application of principles of chemical engineering at scales from the molecular level to the process level.

Ice Cream Science. There are three categories of ingredients in the ice cream mix: dairy, sweeteners, and additives. Milk, cream, and nonfat milk solids make up the dairy portion of ice cream. Sucrose or Splenda® is used to sweeten the mix, and stabilizers and emulsifiers are added to give the ice cream the desired body and mouth feel. Significant quantities of air are also present in finished ice cream. Standard ice cream contains an equal volume of mix and air, or an "overrun" of 100%. Premium ice cream, however, has an overrun of only 80% to give it a richer, more-creamy, mouth feel.

Milk is a colloidal suspension of water, fat, and milk solids. Fat particles in the suspension range in size from 0.8 to 20 μm. The sugar—lactose—is also present in milk, at a concentration of about 4.9%. In "lactose-free" ice creams, the milk is treated with the enzyme lactase, which breaks lactose down into the simpler sugars glucose and galactose.

In this design, regular table sugar, or sucrose, is used as a sweetener in all the ice cream mixes except the low-carbohydrate ice cream. Sucralose is used to sweeten the low-carbohydrate ice cream because it is indigestible but still sweetens the mix.

Stabilizers and emulsifiers are essential in the production of ice cream products. Both components help to give ice cream a smooth body and texture and help to improve the overall mouth feel of the ice cream. Stabilizers work by reducing the amount of free water in the ice cream mixture. This retards ice-crystal growth during storage and also provides resistance to melting. Stabilization is accomplished through two mechanisms, depending on the type of stabilizer used, and both mechanisms may be involved depending on the structure of the gum used. Charged gums, such as carageenan, help to reduce the amount of free water because the charged groups interact with water to restrict the movement of water molecules within the mixture. Branched gums, such as guar gum, also reduce free water within the system. This is accomplished because the branched side chains contain hydroxyl groups that hydrogen-bond with water, a reaction that also reduces the amount of free water. Similarly, emulsifiers help to reduce fat-globule coalescence by stabilizing the fat globules within the ice cream matrix. Mono- and diglycerides are the most commonly used emulsifying agents. The addition of stabilizers and emulsifiers is particularly important for ice cream base mixes that are lower in fat content, because whole milk already contains natural stabilizing and emulsifying materials.

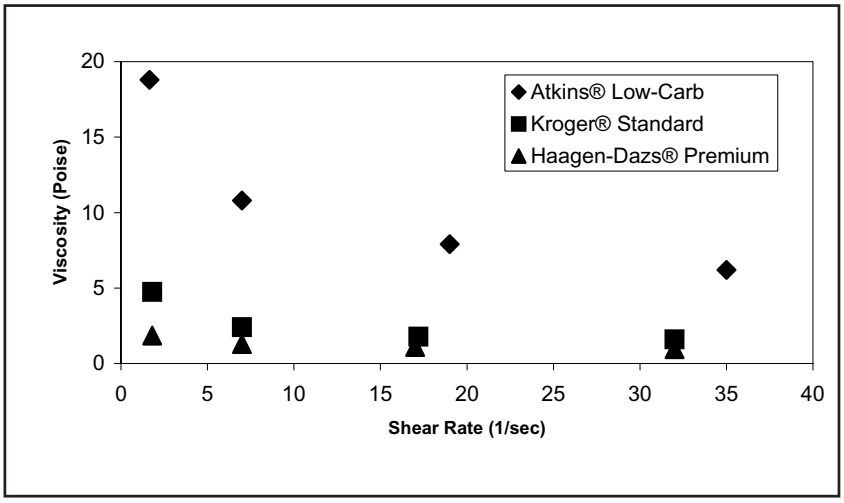

Figure 1. *Viscosity of different ice cream products.*

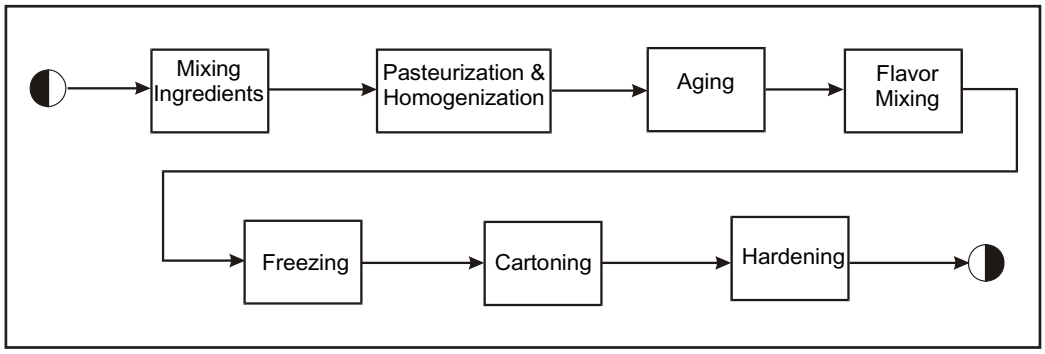

Figure 2. *Block flow diagram for ice cream production.*

The viscosity of ice cream varies with the type. During a class tour of a local ice cream production facility, the host remarked that production of low-carbohydrate ice cream was "difficult on the equipment," which had been placed into operation before low-carbohydrate ice cream was developed. Further investigation revealed that many ice creams, particularly the low-carbohydrate vanillas, contain TiO_2 pigments to make the ice cream look whiter. It is possible that the TiO_2 colloidal particles cause erosion of process equipment. Students also wondered whether there was a variation between viscosities of different ice cream types. One student, who was doing research in the polymer research laboratory of our colleague Rakesh Gupta, measured the viscosity of three types of ice cream. The results are shown in Figure 1. Low-carbohydrate ice cream is clearly more viscous than standard ice cream.

Facility Design. A facility to manufacture, store, and ship ice cream was designed. Production volumes were 52 million 1.75-quart ice cream containers (varying flavors), 2.3 million six-packs of sandwiches, and 4.3 million six-packs of pops (ice cream bars with sticks). The manufacturing process of the ice cream facility is broken down into seven steps, as illustrated in Figure 2. A 5400-m^2 warehouse for ice cream storage was also designed. It was designed to hold three months of production. Because of the need to refrigerate the warehouse, the construction requires special insulation, and the capital investment for this part of the process (>80%) dominates the overall fixed capital investment (almost $100 million)—a result that was not anticipated.

Refrigeration Cycle. Refrigeration (600 tons) is required three places: in the warehouse, in the hardening step in ice cream production, and for cooling the milk at the front end of the process. An ammonia refrigeration-cycle design, used for the warehouse, is displayed in Figure 3. The refrigeration cycle is a traditional chemical engineering component of this design. Using the number of interstage coolers on the compressors and the type of cooling medium used in E-101 through E-104 as decision variables, students optimized the refrigeration process.

Steam Generation. In the facility, low-pressure steam is used for pasteurization, for jacketed heating of the mixing equipment, and for heating water for equipment cleaning. These steps are necessary to ensure that there is no product contamination by bacteria, which is part of "good manufacturing processes" in food production. Therefore, a typical steam-production facility was designed.

Wastewater. A system was designed to process wastewater from the ice cream manufacturing facility. There were two reasons for this. First, it was assumed that the ice cream plant would produce too much additional wastewater for an existing municipal wastewater facility. Second, based on information from the local water authority, having a water treatment facility in-house appeared to be the less-expensive option. Wastewater treatment is needed because the equipment must be cleaned daily, generating significant amounts of wastewater. The operation plan involves production on two

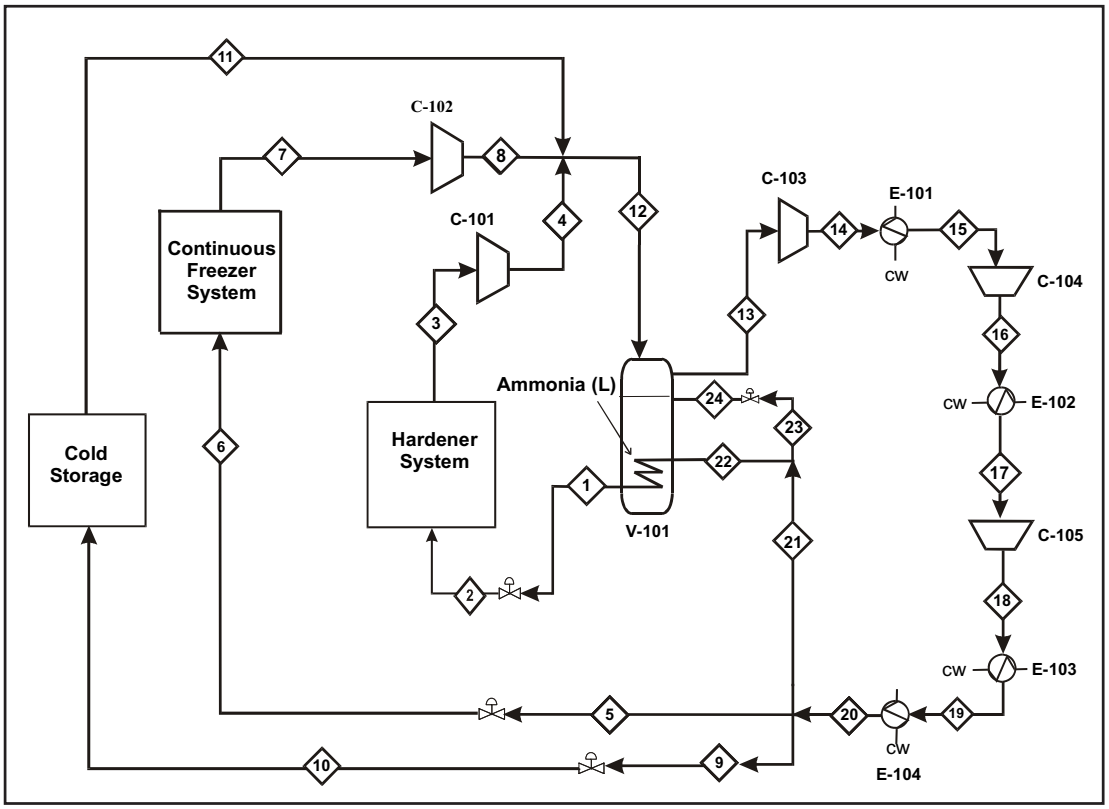

Figure 3. *PFD for the optimized ammonia refrigeration system unit 1.*

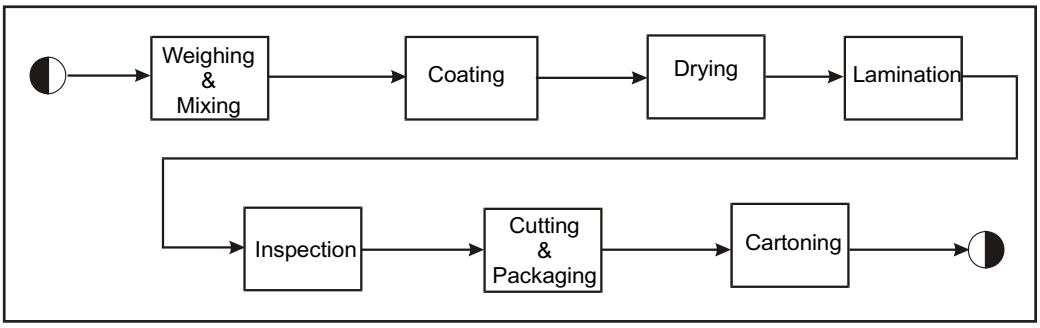

Figure 4. *Block flow diagram for transdermal drug delivery patch manufacture.*

shifts per day followed by a cleaning shift. Most of the cleaning is done using hot water.

Economics. It costs approximately $0.56 to produce a 1.75-quart container of ice cream, including the initial capital investment. Even with the markup associated with the food distribution chain, the process is very profitable. The net present value (NPV) was found to be $97 million, assuming a 10-year plant lifetime and a 15% before-tax rate of return. A Monte Carlo analysis showed that there is only an 8% chance of losing money, *i.e.*, an NPV less than zero. Remarks from an ice cream expert at the final student presentation indicated that prices for milk products could vary over a wide range, leading to significantly greater variation in the NPV. These factors were not considered in the students' analysis but could easily be incorporated.

DESIGN OF A TRANSDERMAL DRUG DELIVERY SYSTEM

This project was completed by 11 students over the course of the entire 2003-04 academic year. It also started with a very open-ended assignment: to investigate alternative forms of drug delivery, and to suggest a product to be manufactured. Within the transdermal patch category, students learned the properties that make a drug suitable for use in a transdermal patch, which are: (1) low molecular weight, (2) high potency, so low dosage required, (3) resistance to enzymes in skin layers, and (4) desire to have constant dosage in body over time. Item number 4 means that a transdermal patch would not be used to treat a simple headache, because, for a headache, rapid entry of the drug into the blood is desired. Students used product-screening methods to choose between alternative drugs.[7] Ultimately, production of a contraceptive transdermal patch for females was chosen for a complete design.

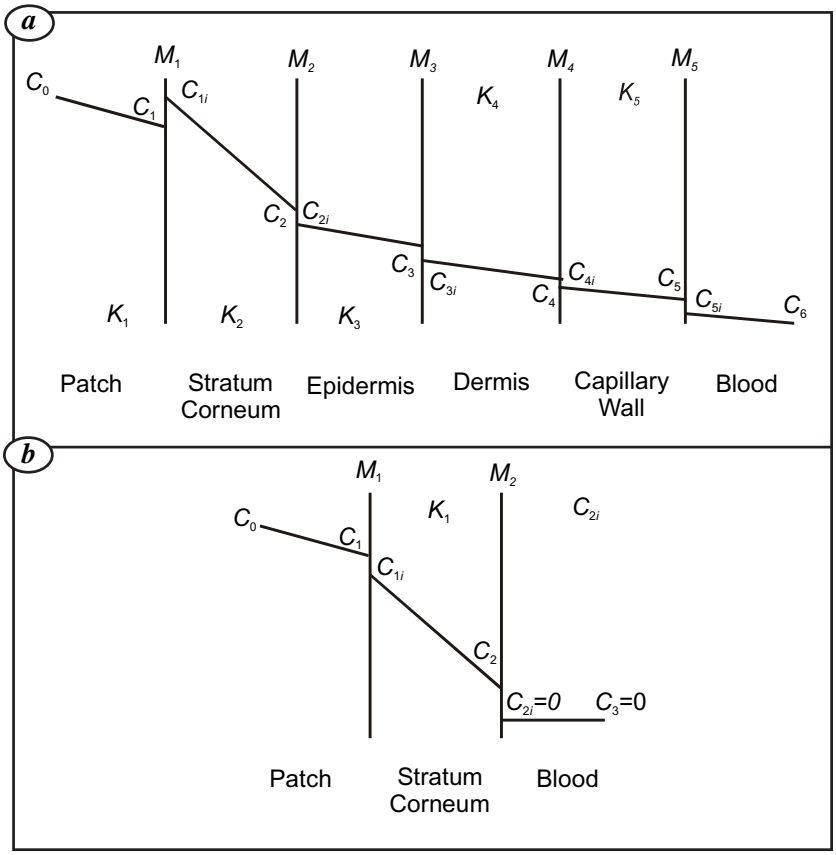

Figure 5. *Model for diffusion through skin layers.*

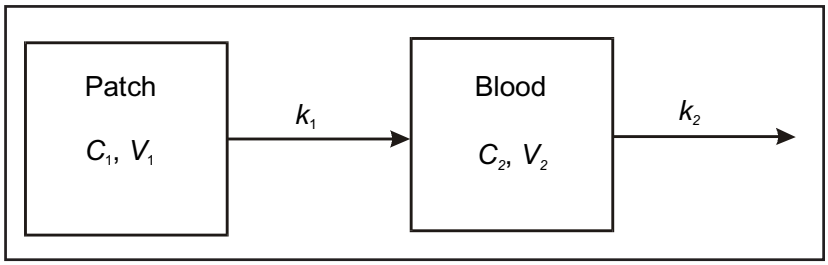

Figure 6. *Two-compartment pharmacokinetic model.*

Patch Design. The patch contains norelgestromin and ethinyl estradiol. The proposed size of the patch is 10 cm^2, manufactured as a single-layer, matrix system.

Pressure-sensitive adhesives are the common form of adhesive used in transdermal systems. They are permanently tacky at room temperature, they are easily applied with light pressure, and they do not require solvents for activation. Polyisobutylene was chosen because it provides excellent adhesion in high-moisture environments and because of its low cost. Polyisobutylene has a surface tension of 30-32 dyne/cm, which is lower than the critical surface tension of skin of 38-56 dyne/cm, depending on humidity and temperature. Therefore, the adhesive will wet the skin—a requirement for adhesion. This is an example of colloid-scale considerations in the transdermal patch design.

Skin penetration enhancers increase the mass flux of a drug across the desired surface area. The driving force for the drug is the concentration gradient between the patch and the skin. The enhancer used in this patch is crospovidone, which draws water to the surface of the skin. This in turn causes swelling, which provides more surface area for diffusion.

Excipients are ingredients within a drug product that are considered inactive, from a pharmacological perspective. In this case, there is one excipient used, propylene glycol monolaurate, which acts as an emollient.

Manufacturing. The block flow diagram for manufacture of the transdermal patch is shown in Figure 4. It is a batch operation. First, the ingredients must be weighed and mixed. The drugs are mixed with the adhesive. The appropriate mixing time and impeller arrangement are estimated using typical chemical engineering principles.[8] Then, the mixture is coated on the backing. Hexane is used as a solvent to help lower the viscosity of the solution and to ensure a well-mixed product. After coating, the hexane is evaporated and is subsequently incinerated, because it was determined that there was not enough hexane present to justify a recovery system. Next, the release liner is added to sandwich the drug/adhesive mixture. After inspection (as required by law) large sheets are cut into 10 cm^2 patches, packaged individually, and then packaged again, three per carton. Finally, cartons of the three-packs are packaged for distribution.

Part of the design involved identifying "good manufacturing practices" in the pharmaceutical industry, which ensure that the product is pure and free of contamination.

Economics. Students determined that the cost of manufacturing one patch is between $0.28 and $0.30, depending on employee salaries and the plant location. The U.S. pharmacy price for a similar, brand-name product is approximately $15 per patch. Since this product is to be a generic version, it was assumed that its price would be about half of the brand-name product. The markup at the pharmacy is assumed to be twice the price for which it was purchased. Therefore, the estimated manufacturer's patch price is $3.75. Selling the patches for $3.75 per patch yields a net present value of $684 million assuming a 10-year plant lifetime and a 15% before-tax rate of return. No information was available from industry sources to verify these assumptions or the resulting NPV estimate.

A . . . goal is to make students realize that they will have to continue learning new material throughout their careers, and that they have the ability to do so.

Mathematical Modeling. In the design of a transdermal patch, the dose is a key factor to consider. The drug is delivered from the patch to the body by diffusion through the multiple layers of skin, so students were required to model diffusion through multiple, immiscible layers. The flux of a given drug from a transdermal system into the body can be modeled as shown in Figure 5a. The result is

$$j=\frac{C_0-\frac{C_n}{\prod M_j}}{\frac{1}{K_0}+\sum_{j=1}^{n}\frac{1}{K_j\left(\prod_{j=1}^{n} M_j\right)}} \tag{1}$$

where C_0 is the concentration of the drug in the patch, K_j is the inverse of the resistance to diffusion of the drug provided by each skin layer, and M_j is the partition coefficient of the drug between a layer and the subsequent layer ($M_j = C_{ji}/C_j$). It was found that the rate-limiting step is diffusion through the stratum corneum layer. So, if it is assumed that the concentration in the blood is zero ($C_n = 0$), the model reduces to Figure 5b, and Equation (1) becomes

$$j=C_0K_1M_1 \tag{2}$$

A pharmacokinetic model was also developed, which can be used to predict the concentration of the active ingredients in the blood. The model is illustrated in Figure 6, and the equations are

$$\frac{dC_1}{dt}=\frac{-k_1C_1}{V_1} \tag{3}$$

$$\frac{dC_2}{dt}=\frac{k_1C_1-k_2C_2}{V_2} \tag{4}$$

where C_1 is the concentration of an active ingredient in the patch, k_1 is the elimination rate constant from the patch, V_1 is the volume of the patch, C_2 is the concentration of the active ingredient in the blood, k_2 is the elimination rate constant from the blood, and V_2 represents the volume of blood in which the drug is distributed. Students fit this model to published data to determine the values of k_1 and k_2.[9, 10]

Multiscale Design. In terms of multiscale analysis, design of a transdermal drug delivery system requires design from the molecular scale through the macroscopic scale. These

items are summarized in Table 2. At the molecular scale, the drug itself is designed. This is beyond the scope of this project. At either the molecular or nano scales, one finds the presence of excipients and/or enhancers in the patch. The adhesive to hold the transdermal patch to the skin could involve design at multiple scales. Since the drug is mixed with the adhesive, if there were a molecular interaction between the drug and adhesive, it would have to be understood. For an adhesive to stick, it must wet the skin, so an understanding of colloid-scale wetting phenomena is required. The patch must be removed without significant discomfort, yet not become detached in the shower or during physical activity that causes sweating—both macro-scale phenomena. At the microscopic scale, the mechanism of transport of the drug through the skin must be understood. Modeling drug transport through the skin layers is standard transport phenomena. Similarly, there is system modeling, in which the pharmacokinetics of the drug in the body can be modeled. Finally, at the macroscopic scale, the components must be combined appropriately, manufactured into the desired product, and packaged for sale.

TABLE 2
Length Scales and their Application to the Transdermal Patch Problem

nano scale	the action of enhancers and excipients at a molecular level on the skin surface
colloid scale	mechanism of adhesion
micro scale	transdermal transport phenomena
	pharmacokinetics
macro scale	product manufacture

ASSESSMENT

Two assessment measures were used. In one, the two instructors use a rubric to evaluate, separately, all aspects of the final design report and oral presentation submitted by the students each semester. This rubric was developed in the context of more traditional chemical engineering design problems. For example, since biology is not (yet) required in our curriculum, it is not listed as a science that students are expected to demonstrate an ability to apply. The ability to learn and to apply biological concepts as needed is evaluated under the ability to learn new material not taught in class. The complete rubric is available on the Web.[11] Table 3 shows the results, averaged for the two instructors, for both projects. The score of three indicates *meets expectations*, and the score of four indicates *exceeds expectations*. Clearly, our assessment of the students suggests that they exhibited superior performance in the ability to teach themselves new material.

In our student evaluation of instruction, it is possible for the instructor to add an individually defined question. Table 4 shows several such questions and the student responses. The responses are on a 5-point Likert Scale, thus indicating student responses were all between "agree" and "strongly agree." Therefore, we conclude that the students involved in these projects believed them to be beneficial.

DISCUSSION

One of the advantages of a project such as ice cream production is that it has traditional chemical engineering components (*e.g.*, refrigeration cycle, wastewater treatment, steam production) along with multiscale considerations, product design and manufacture, and packaging. Design of a transdermal drug patch has a stronger life science component and involves more transport phenomena-oriented mathematical modeling (*i.e.*, systems analysis) than a traditional chemical process design.

While the multiscale aspects of these projects have been identified, the molecular-scale phenomena have not yet been incorporated into the design. For example, we do not believe that we are in a position to design a new drug or to manipulate the microstructure of ice cream. If, however, a product design assignment were based on a faculty member's research, it might be possible to include molecular-, nano-, or colloidal-scale design aspects, especially if students were in a position to perform experiments.

A reasonable question is what other design projects of this type are envisioned. The list of potential life science-related projects is long and could include innovative drug-delivery devices (*e.g.*, drugs on a chip) or tissue growth. Our class of 2003 designed a facility for the batch production of amino acids.[5] Design of a microprocessor production facility would involve multiscale phenomena and could also involve traditional chemical engineering in the production of ultra-pure water and in wastewater treatment. Design of an advanced material based on its micro- or nano-structure is also possible. The importance of multiscale phenomena in paper manufacture was recently presented,[12] so manufacture of fine paper products is a possibility.

More detailed synopses of these projects are available on our design project Web site.[5] The final reports are also available to faculty members by contacting the authors.

CONCLUSIONS

As the profession of chemical engineering moves toward product development and design and away from process development and design, a new paradigm for chemical engineering education is evolving, requiring a new generation of capstone design projects. Two examples have been presented here. In ice cream manufacture, multiscale considerations are important, yet there are traditional chemical engineering components included. Production of other food products involves

many of the same considerations. In design of a transdermal drug delivery patch, life science considerations, multiscale factors, and systems modeling are required. Both involve aspects of product design. They also require manufacture and packaging of unit items—topics traditionally foreign to chemical engineering education. As the chemical engineering curriculum changes in response to the changes in our profession, similar design projects will find their way into capstone experiences.

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TABLE 3
Assessment Results for Design Projects

Assessment	Patch	Ice Cream
Design of equipment, understand interrelationship between equipment in process	3.0	3.0
Apply chemistry, math, physics, engineering science	3.5	3.5
Resolve complex problem into components	3.0	3.5
Apply economic, physical constraints, and optimization methods to obtain solution	3.0	3.0
Use of computer-based and other information systems	3.0	3.0
Demonstrate ability to learn new material not taught in class	4.0	4.0
Demonstrate ability to function in assigned role	3.0	3.0
Demonstration of ethical behavior	3.0	3.0
Demonstrate understanding of societal impact and need for assigned design	3.0	3.0

TABLE 4
Student Evaluation of Instruction Results

Result	Group Asked	Out of 5.0
Tackling the nontraditional problem posed in the large-group project enhanced my confidence in solving new problems.	Patch	4.90
I feel that my experience with the group design taught me the importance of and the need for continuously learning new material.	Patch	4.17
In my career, I will be required to solve problems appearing to be outside the mainstream of chemical engineering, such as food processing.	Ice cream	4.17
I feel confident that I can apply my chemical engineering knowledge to any application.	Ice cream	4.40
The teamwork experience in this class will be valuable in my future career.	Ice cream	4.57